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COMBUSTION TERMINATION SYSTEM FOR 120-INCH-DIAMETER SOLID ROCKET MOTOR (TITAN III-C)

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UNITED TECHNOLOGY CENTER

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AIR FORCE ROCKET PROPULSION LABORATORY

RESEARCH AND TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

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FOREWORD

This report was prepared by United Technology Center (UTC), Sunnyvale, California, under Contract No. AF 04(695)-845. The contract was initiated under UTC Project 2157, "Combustion Termination System for 120-in.-Diameter Solid Motor," on 1 July 1965. The work was administered by the Systems Motors Branch (RPMB) of the Air Force Rocket Propulsion Laboratory (AFRPL), Edwards, California, with Captain J. Dell and Lt. R. B. Neely as project officers. This report covers the entire program effort from 1 July 1965 through 30 September 1966. This report was submitted on October 7, 1966.

The data in this report have resulted from the combined efforts of the Research and Advanced Technology and Engineering personnel of UTC. The author wishes to acknowledge the assistance of those who contributed significantly to the program. The task I laboratory tests were planned and conducted by J. K. Kilgroe. The task I TM-1 test program was directed by C. P. Harris and conducted by H. Wolff. The task II TM-3A test program was directed by the author and conducted by G. Stromberg. Technical advice on the theoretical aspects of the program was obtained frequently from Dr. R. Anderson and Dr. R. S. Brown.

This technical report has been reviewed and is approved.

Charles R. Cooke
Acting Chief, Solid Rocket Division

ABSTRACT

This is the final report covering the experimental and analytical work performed by UTC on Air Force Contract AF 04(695)-845. The original purpose of the program was to develop a liquid injection combustion termination system for the 120-in. -diameter (Titan III-C) solid rocket motor (SRM). The program was subsequently modified to include further study of the fundamental phenomena involved in the combustion termination process and the development of injector techniques and grain configurations applicable to the extinguishment of all types of segmented SRMs.

During the course of the program, a total of 56 motor firings was conducted to evaluate injectant materials, injection systems, and propellant charge configurations. These tests were conducted in motors ranging in size from a 0.5-lb laboratory motor to a two-segment TM-3A motor containing over 500 lb of propellant. In addition, 22 cold-flow tests were conducted to investigate injectant dispersion patterns of various injector configurations.

As a result of these tests, it was established that solid propellant motors cast with PBAN (polybutadiene acrylonitrile) propellant could be extinguished by injecting a liquid into the combustion chamber. The mechanism controlling the extinguishment of PBAN was determined to be heat transfer. For this reason, water, with its high specific heat, proved to be the most effective injectant, and the necessity of contacting all burning surfaces by the injectant was established. Radial slots in the propellant charge downstream of the injector were found to be particularly difficult to contact with injectant and were therefore subject to reignition. For this reason, a reliable system for extinguishing the Titan III-C configuration was not developed.

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SYMBOLS

A_B	propellant burning surface area, in.^{2}
A_t	nozzle throat area, in.^{2}
C_D	flow coefficient
dp/dt	pressure decay rate, psi/sec
D_t	nozzle throat diameter, in.
P_c	chamber pressure, psi
$(P_c)_{inj}$	motor chamber pressure at the time of injection, psi
t	burn time, sec
W_{inj}	weight of injectant charge, lb
$\dot{w}_{inj}$	injectant flow rate, lb/sec
$\dot{w}_{motor}$	motor propellant mass flow rate, lb/sec
W_p	propellant weight, lb
$\Delta H_{inj}/\Delta H_{water}$	total heat enthalpy ratio
ΔP	pressure drop, psi

SECTION I

INTRODUCTION

Contract AF 04(695)-845 was initiated at UTC on 1 July 1965 for the purpose of developing a liquid injection combustion termination system for the Titan III-C 120-in. -diameter SRM. This task included development testing in laboratory, TM-1 and TM-3A size motors, with the final demonstration test series in a one-segment 120-in. -diameter motor. This contract was subsequently amended by Supplemental Agreement No. 2, which deleted the requirement for the 120-in. -diameter demonstration tests and modified the requirements for the subscale tests to allow investigation of several propellant grain configurations.

This report presents a comprehensive coverage of the entire experimental and analytical effort on the program and is issued as a final documentary report in fulfillment of the contract.

The program for the development of the combustion termination system for the Titan III-C 120-in. -diameter SRM was directed toward a study of the phenomena of liquid injection combustion termination and the establishment of theories and criteria necessary for the design of combustion termination systems.

The program was divided into four basic engineering tasks. Task I of this program provided for design and analytical studies and for the firing of laboratory and small (TM-1) rocket motors. The effects of various parameters on the combustion termination characteristics of solid propellant rocket motors were determined, and the criteria necessary to design the termination system for a TM-3A rocket motor were established. In task II, TM-3A motors were tested using the injectant and injector selected during task I. The effects of varying the injector flow parameters were investigated, and the importance of grain configuration was established. In task III, the preliminary processing of the motor hardware preparatory to the 120-in. -diameter motor demonstration test was completed. Task IV provides all documentation required in support of the contract.

SECTION II

SUMMARY

This report covers the entire program effort from 1 July 1965 to 30 September 1966. During this period, 22 injector cold-flow tests, 24 laboratory motor firings, 24 small motor (TM-1) tests, 6 TM-3A injector cold-flow tests, and 8 TM-3A motor tests were conducted. A PBAN propellant was used in all motors, and successful extinguishments were accomplished in the laboratory, TM-1, and one-segment TM-3A motors.

Initial laboratory motor tests were conducted to demonstrate the feasibility of a head-end pintle injector design concept and to acquire data necessary for the designs of the small motor (TM-1) tests. Four laboratory motor firings, using water as injectant, were conducted for this purpose. The first three were not successful in completely terminating combustion. Posttest evaluation of the propellant grains in two of the tests, made possible by total extinguishment with a secondary system, indicated that it is essential to obtain complete coverage of the propellant surface with injectant in order to accomplish total extinguishment. Minor injector modifications to obtain a better injectant spray pattern were made, and total extinguishment was achieved on the fourth test.

Twenty injectant survey tests were conducted to compare the relative effectiveness of several candidate injection fluids with water. Injectants tested included: (1) water containing surface active agents, (2) water containing a suspension of carbon black, (3) a solution of water and ammonium bromide, (4) Freon 114B-2, and (5) nitrogen tetroxide (N_2O_4). Freon 114B-2 and N_2O_4 were tested because they are currently used on several rocket motors as TVC fluids and might serve a dual purpose as a combustion termination injectant. The solutions of carbon black and ammonium bromide were investigated because of the increase in heat capacity they would give to the bulk fluid. The surface active agents were used because of a postulated increase in fluid effectiveness as a result of the decrease in fluid surface tension.

Test results indicated that only the water with a surface wetting agent added might show some advantage over water as an injectant. Although the solutions of carbon black and water and ammonium bromide and water increased the total heat capacity of the bulk fluid, no performance improvement was attained when compared to water on a weight basis.

Serious motor overpressurizations were noted on tests using Freon 114B-2 and N_2O_4 as injectants.

Twenty-four TM-1 firings were conducted with three basic injector types and two propellant grain configurations. Water was used as the injectant on these tests. The injection system design incorporated a positive displacement cylinder driven by high-pressure gaseous nitrogen (GN_2). This system allowed for the use of three basic injector types: (1) conventional single-orifice injectors capable of full- or hollow-cone spray patterns, (2) movable pintle designs with a sweeping spray pattern, and (3) piccolo injectors with multiple orifices. Each type of injector was shown to be capable of completely extinguishing combustion for a characteristic set of injectant flow parameters regardless of the grain configuration.

Evaluation of TM-1 test data indicated that a critical injection rate and injectant quantity existed for a given motor test condition. Using this fact, it was found that two parameters could be used to define the critical injection mode for varying motor test conditions. These parameters were the ratio of average injectant mass flow rate to motor propellant mass flow rate ($\dot{w}_{inj}/\dot{w}_{motor}$) at the initiation of termination and the total injected mass per propellant burning surface area (W_{inj}/A_b) required for complete extinguishment.

Quantitative design laws were established for the TM-1 motors which were subsequently used in the design of the injection system for the larger TM-3A motor tests.

Six injector cold-flow tests and eight extinguishment tests were conducted in three configurations of the TM-3A test motor. Each configuration was a modification to the basic Titan III-C grain design. Water was used as the injectant, and the injection system design incorporated a positive displacement cylinder driven by high-pressure GN_2 and a movable pintle injector.

The requirement for complete coverage of all propellant surfaces indicated in the laboratory motor tests was verified in the TM-3A tests. The aft slot, between the segment propellant and the aft closure propellant, proved to be the most difficult area to contact with injectant in each of the motor configurations, and incomplete extinguishment in this area resulted in motor reignition in five of the eight extinguishment tests.

Changes were made to the basic Titan III-C grain configuration during the test series in an effort to improve the dispersion of injectant into the slot area. These changes did not alleviate the problem, and a reliable means of extinguishing segmented motors was not developed.

These changes showed some promise in the cold-flow tests; however, counter-flow conditions, caused by mass evolution from the slot, apparently have a significant effect on the flow of injectant through the motor and result in reducing the amount of water that is deflected into the slot area.

On the basis of the test results, it was concluded that the process of combustion termination of PBAN propellant by liquid injection is one of heat transfer; i. e., the injectant contacts the propellant surface and by heat transfer cools the surface below its autoignition temperature. The pressure decay rate (dp/dt) obtained in these tests does not have any apparent effect on extinguishment.

SECTION III

TECHNICAL DISCUSSION

3.1 SMALL MOTOR TESTING

A total of 24 laboratory motor tests and 24 TM-1 motor tests were conducted during the small motor test program. Tests were conducted in both motors concurrently. The laboratory tests were conducted primarily for injectant evaluation, and the TM-1 tests were conducted for injector evaluation.

3.1.1 Laboratory Tests

Laboratory testing included 22 cold-flow tests to establish the injector dispersion patterns, 4 preliminary motor firings to establish the feasibility of an injector concept for use in the small motor test program, and 20 firings for injectant evaluation. A summary of laboratory test results is presented in table I. Injectant charge weight and flow rate was varied as required to evaluate the various injectant and injectors.

3.1.1.1 Test Apparatus Description

An existing UTC laboratory propellant study motor (shown in figure 1) was modified to permit studies of combustion termination by liquid injection. This motor consists of a stainless steel box 8-1/2 in. long, 4 in. wide, and 4 in. deep. This motor utilizes a slab of propellant with a surface area of approximately 11.25 $in.^2$ The propellant is contained in a strainless steel tray which can be placed in the motor such that the burning surface, which corresponds to approximately two-thirds of the motor length, may be positioned at either the forward or aft end of the motor. Injection ports were machined into the motor at the forward end and on the side opposite the propellant.

The propellant used on all test firings was UTP-3001, a composite propellant system containing ammonium perchlorate and aluminum with a polybutadiene acrylic acid/acrylonitrile (PBAA/AN) binder. A detailed description of the propellant including its physical and ballistic properties is available.[1]*

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* Superscript numbers denote references appearing on page 177.

TABLE I

LABORATORY MOTOR FIRINC

Test No.	Injector	Injectant	W_{inj} lb	$\dot{w}_{inj}$ lb/sec	$(P_c)_{inj}$ psi	$\dot{w}_{motor}$ lb/sec	$\dot{w}_{inj}/\dot{w}_{motor}$	W_{inj} lb/
001*	Pintle, Mod A	H_2O	0.071	1.42	382	0.204	6.97	0.0
002*	Pintle, Mod A	H_2O	0.071	1.42	375	0.204	6.97	0.0
003*	Pintle, Mod B	H_2O	0.071	1.42	380†	0.204	6.97	0.0
004	Pintle, Mod B1	H_2O	0.071	1.18	350	0.202	5.85	0.0
005	WSS-F-SS-40-75-S‡	H_2O	0.165	1.34	480†	0.225	5.98	0.0
006	WSS-F-SS-20-75-S	H_2O	0.215	1.15	480	0.225	5.10	0.0
007	WSS-F-SS-20-75-S	H_2O-Sterox	0.115	1.15	480†	0.225	5.10	0.0
008	WSS-F-SS-20-75-S	H_2O-Santomerse	0.145	0.805	480†	0.225	3.58	0.0
009	WSS-F-SS-20-75-S	H_2O	0.182	0.570	480	0.225	2.53	0.0
010	WSS-F-SS-40-75-S	H_2O-NH_4Br	0.217	1.55	450	0.222	6.97	0.0
011	WSS-F-SS-40-75-S	Freon 114B-2	0.403	2.44	490	0.226	10.80	0.0
012	WSS-F-SS-40-75-S	H_2O-Liquiblack	0.213	1.78	480†	0.225	7.90	0.0
013	WSS-F-SS-40-75-S	N_2O_4	0.279	←			No Data	→
014	WSS-F-SS-40-75-S	N_2O_4	0.279	←			Test Aborted	→
015	WSS-F-SS-40-75-S	N_2O_4	0.279	2.10	450	0.222	9.45	0.0
016	WSS-F-SS-40-75-S	H_2O	0.234	1.46	480	0.225	6.50	0.0
017	WSS-F-SS-40-75-NS§	H_2O	0.307	1.54	450	0.222	6.90	0.0
018	WSS-F-SS-40-75-NS	H_2O	0.200	1.54	450	0.222	6.95	0.0
019	WSS-F-SS-40-75-NS	H_2O	0.254	1.58	450	0.222	7.10	0.0
020	WSS-F-SS-40-75-NS	H_2O	0.214	2.46	390	0.204	12.05	0.0
021	WSS-F-SS-40-75-NS	H_2O/Sterox	0.214	1.90	390	0.204	9.33	0.0
022	WSS-F-SS-40-75-NS	H_2O/Sterox	0.200	1.82	405	0.211	8.66	0.0
023	WSS-F-SS-40-75-NS	H_2O/Sterox	0.200	1.72	450	0.226	7.65	0.0
024	WSS-F-SS-40-75-NS	H_2O/Sterox	0.172	1.44	460	0.223	6.56	0.0

* Backup injector used on these tests
† Assumed value; data not valid
‡ S designates that a nozzle swirl plate was used
§ NS designates that the nozzle swirl plate was removed

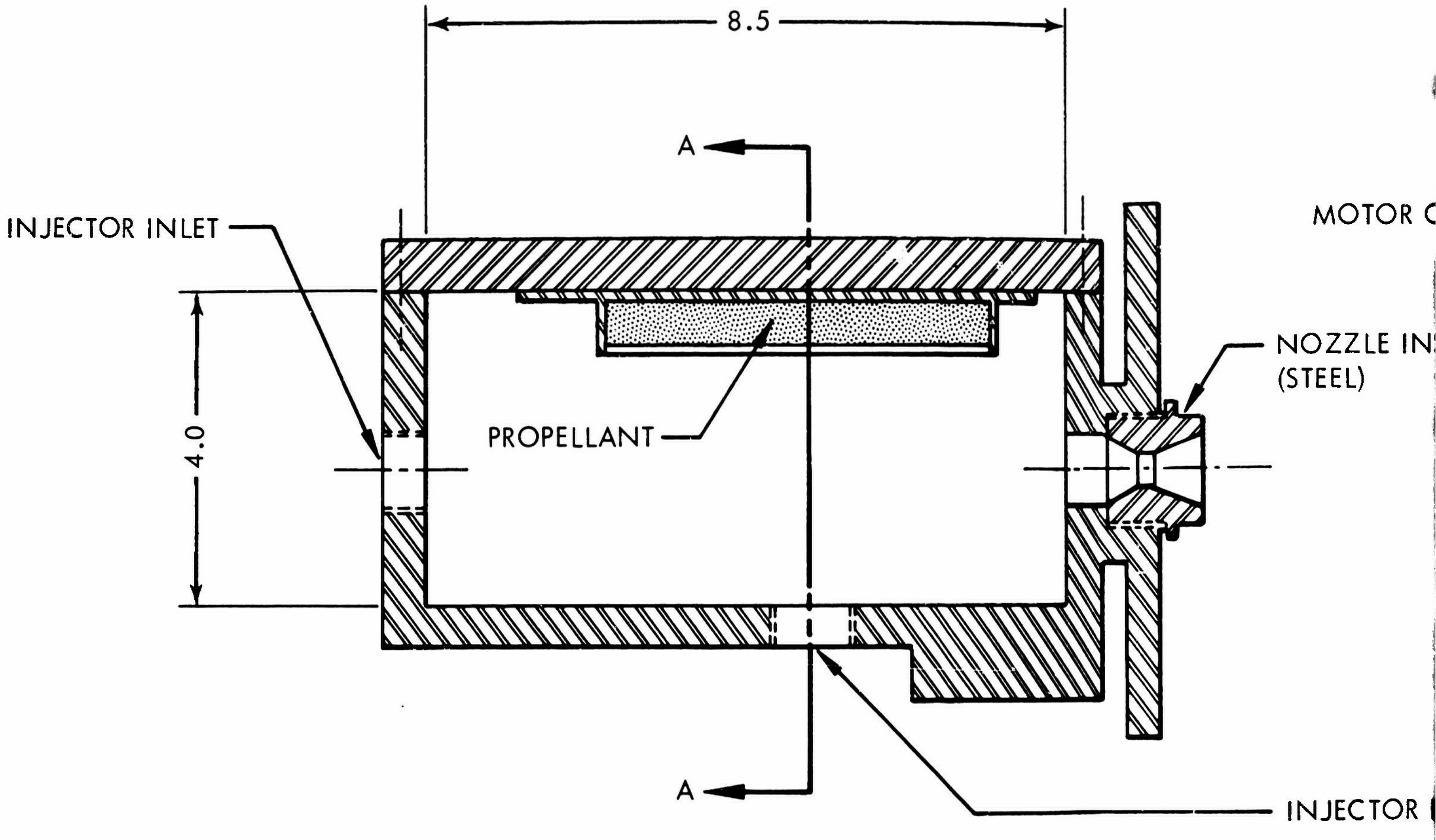
A

TABLE I

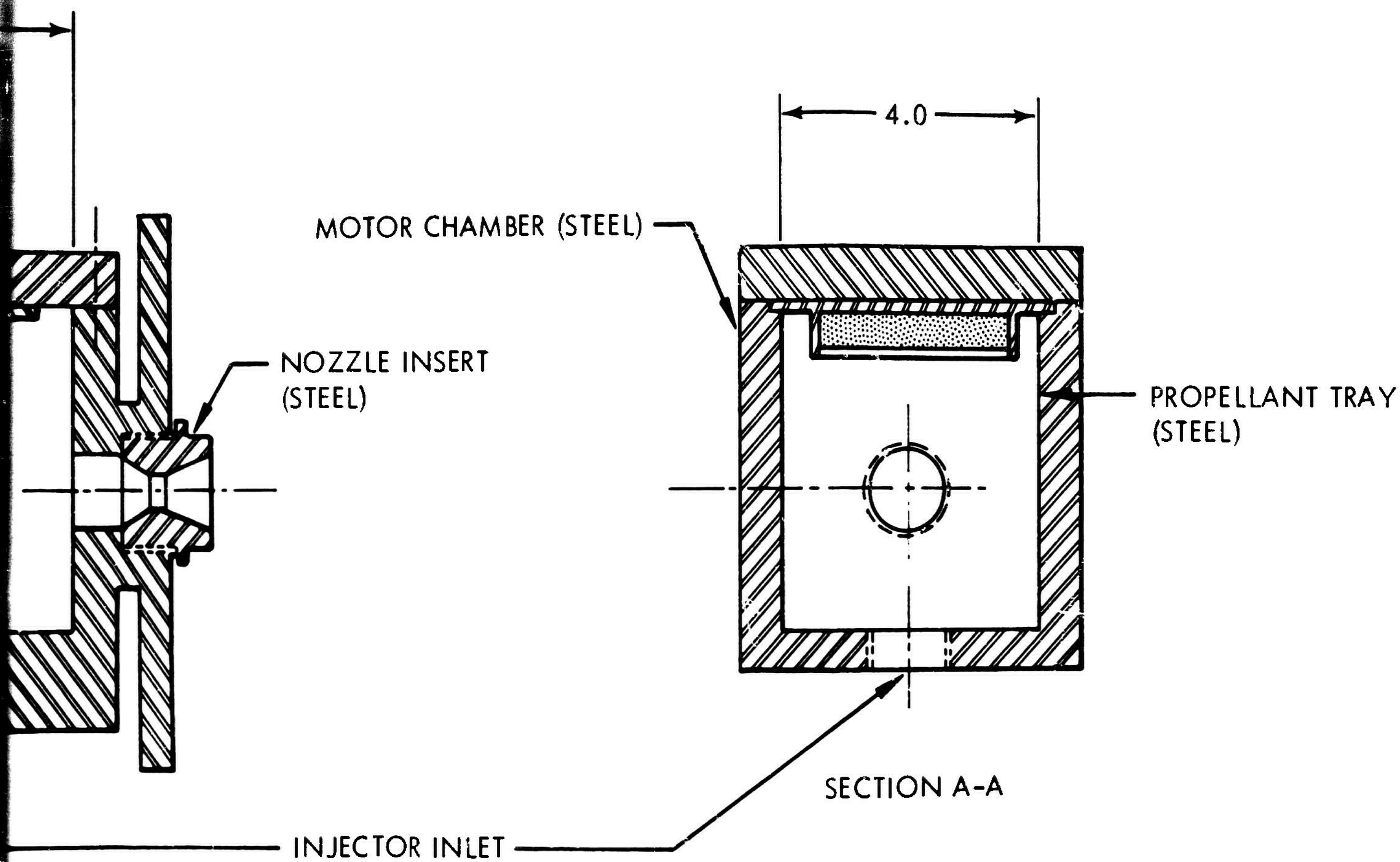
ATORY MOTOR FIRING SUMMARY

$\dot{w}_{motor}$ lb/sec	$\dot{w}_{inj}/\dot{w}_{motor}$	W_{inj}/A_B lb/in.	(dp/dt) psi/sec	Comments
0.204	6.97	0.0063	14,000	No termination -- no injection impingement on portion of surface
0.204	6.97	0.0063	13,000	No termination – no injectant impingement on portion of surface
0.204	6.97	0.0063	---	No termination – no injectant impingement on portion of surface
0.202	5.85	0.0063	3,150	Terminated
0.225	5.98	0.0147	---	No termination
0.225	5.10	0.0191	13,150	No termination
0.225	5.10	0.0102	---	No termination
0.225	3.58	0.0129	---	No termination
0.225	2.53	0.0162	3,780	No termination – injector swirler probably damaged
0.222	6.97	0.0193	8,200	No termination
0.226	10.80	0.0358	33,800	No termination – overpressure blew burst disk
0.225	7.90	0.0189	---	No termination
No Data				No termination – no data because of operator error
Test Aborted				Test aborted – motor did not fire because of blown fuse in sequencer
0.222	9.45	0.0248	29,600	No termination – overpressure blew burst disk
0.225	6.50	0.0208	11,100	No termination
0.222	6.90	0.0273	[illegible],000	Terminated
0.222	6.95	0.0178	5,900	No termination
0.222	7.10	0.0225	6,500	Terminated
0.204	12.05	0.0190	10,870	Terminated
0.204	9.33	0.0190	8,250	Terminated
0.211	8.66	0.0178	7,880	Terminated
0.226	7.65	0.0178	7,560	Terminated
0.223	6.56	0.0153	6,750	Reignited after long delay

B



8.5
A
INJECTOR INLET
MOTOR C
4.0
NOZZLE IN
(STEEL)
PROPELLANT
A
INJECTOR



MOTOR PHYSICAL AND BALLISTIC PROPERTIES

PROPELLANT WEIGHT (W_P), lb	0.5
BURN TIME (t), sec	2.0
CHAMBER PRESSURE (P_c), psi	400 NOM
NOZZLE THROAT SIZE (A_t), in.^{2}	0.075
INITIAL SURFACE AREA (A_B), in.^{2}	11.25

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Figure 1. Laboratory Test Motor

The injection system, shown in figures 2 and 3, selected for use with the laboratory motor utilized a cylinder with a pneumatically driven positive displacement piston to force the fluid through the injector nozzle into the motor. A positive displacement piston-type injector was selected for the laboratory tests for two primary reasons:

A. Injectant charge weight and flow rate could be easily controlled.

B. The piston served to close the injector after the injection phase to prevent the backflow of hot gases into the injector in the event of motor reignition.

The injector cylinder was 7 in. long and 1-3/8 in. in diameter. The injector was fabricated of stainless steel and designed for injector pressures in excess of 2,000 psi.

During testing, the injectant charge was varied by changing the stroke of the piston; the flow rate was varied by increasing or decreasing the GN_2 pressure. A drag rod was attached to the piston and coupled to a linear transducer to monitor the piston travel with respect to time during each run. From this information, it was possible to accurately establish the injectant flow rate throughout the entire run. Several injector nozzle designs were evaluated in the laboratory test series. These can be grouped into the two basic types shown in figure 4.

A. Pintle Injector

The injector shown in figure 4A utilized a moving pintle to disperse the injectant from the motor centerline to the propellant surface. The pintle is attached to the piston so that the pintle movement and injector flow are coordinated to provide uniform injectant distribution over the propellant surface. A swirl plate was located in the injector nozzle to impart a radial velocity to the fluid as it entered the combustion chamber and further encourage the dispersion of injectant to the walls of the motor chamber. This feature was added to the design in anticipation of the TM-3A tests, where injectant dispersion to the motor chamber wall would be required to insure injectant contact with the propellant in the radial slots. Three types of pintle designs (shown in figure 5) were investigated with this injector: (1) a tapered pintle, (2) a straight pintle, and (3) a straight pintle with a splashplate attached to the face. The tapered pintle was designed so that the annular area between the shaft and the injector orifice varied throughout the injection period. Thus, the injectant flow was regulated to be greater at the beginning

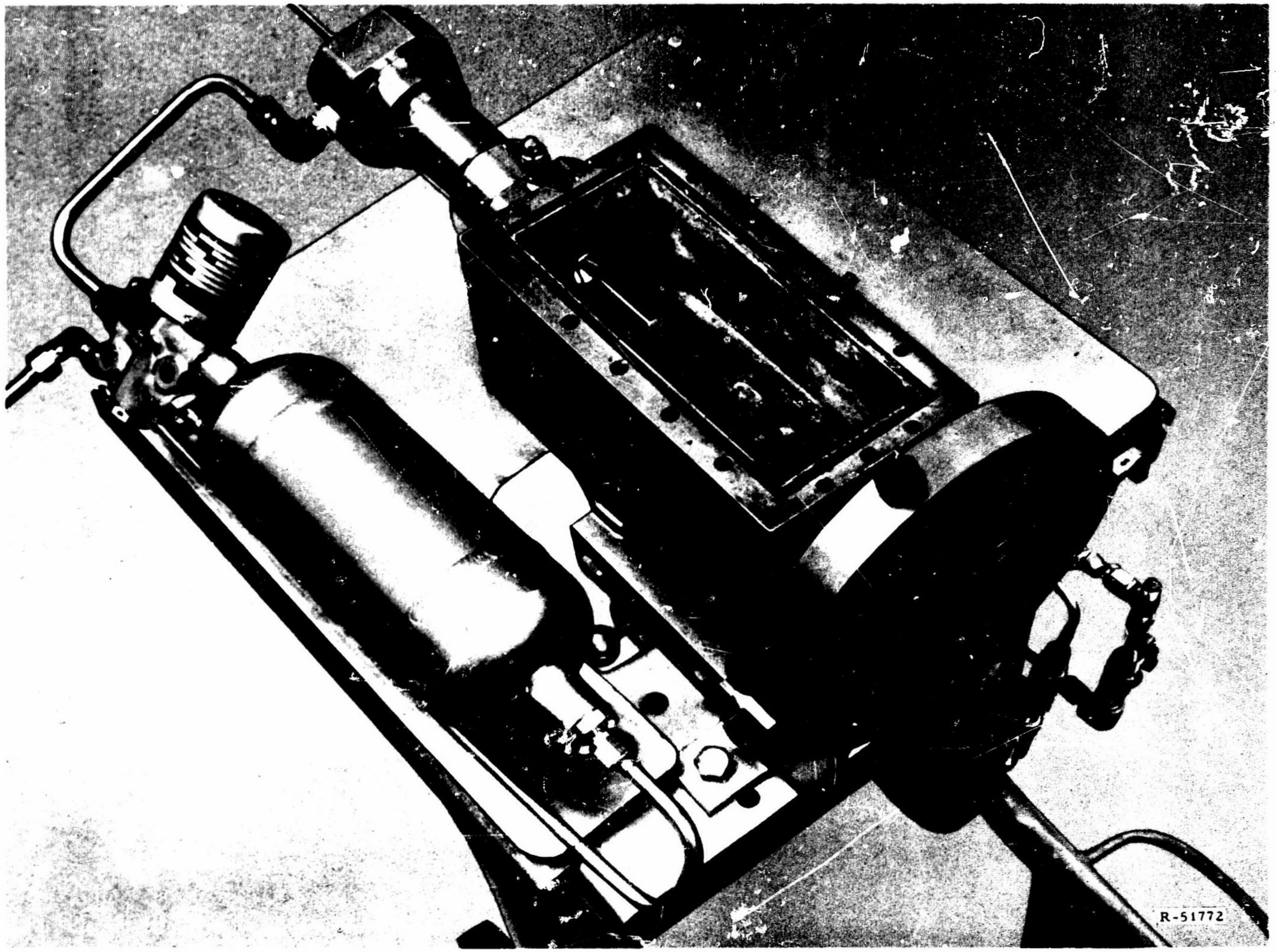

Figure 2. Laboratory Test Motor

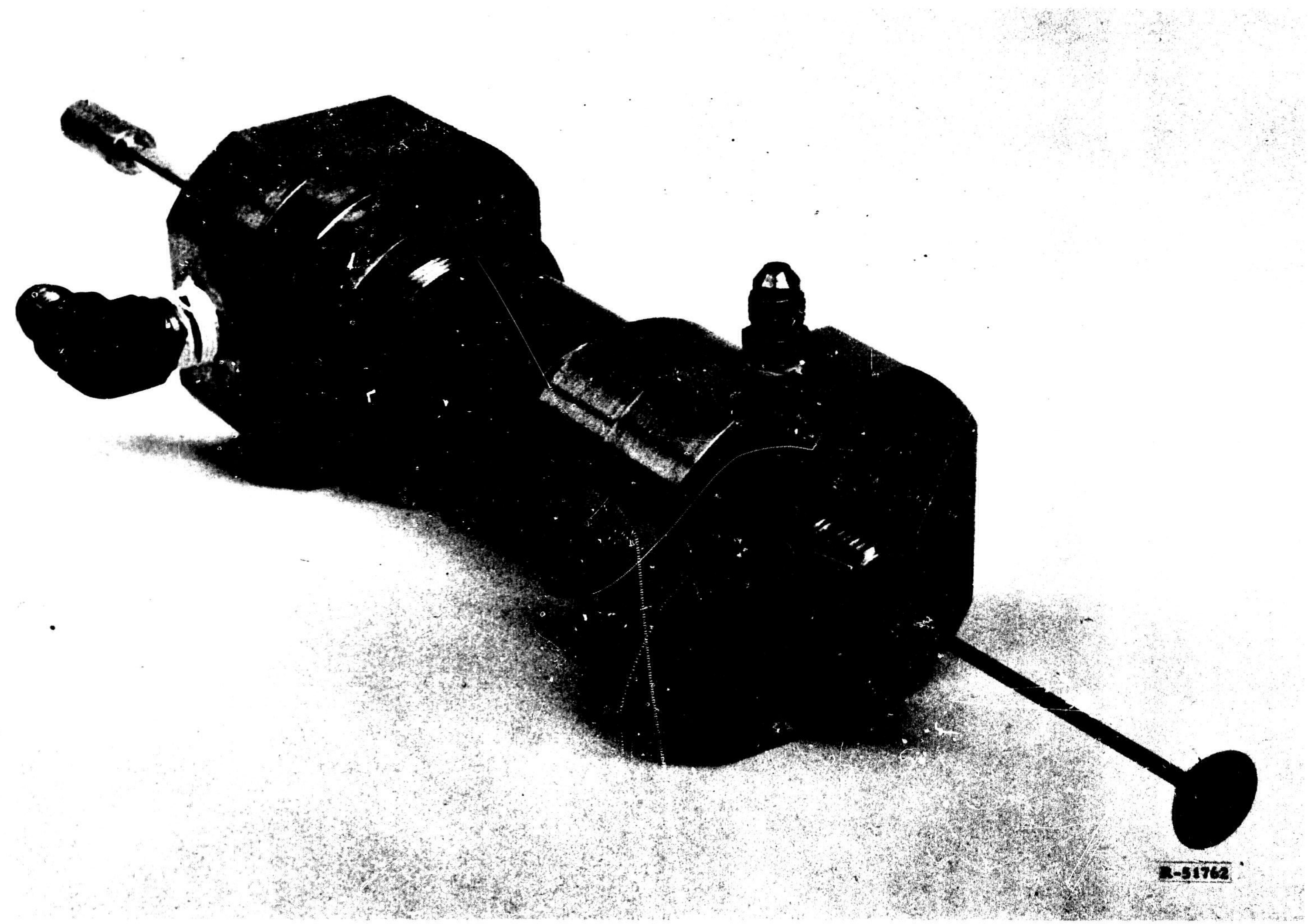

Figure 3. Pintle Injector, Laboratory Tests

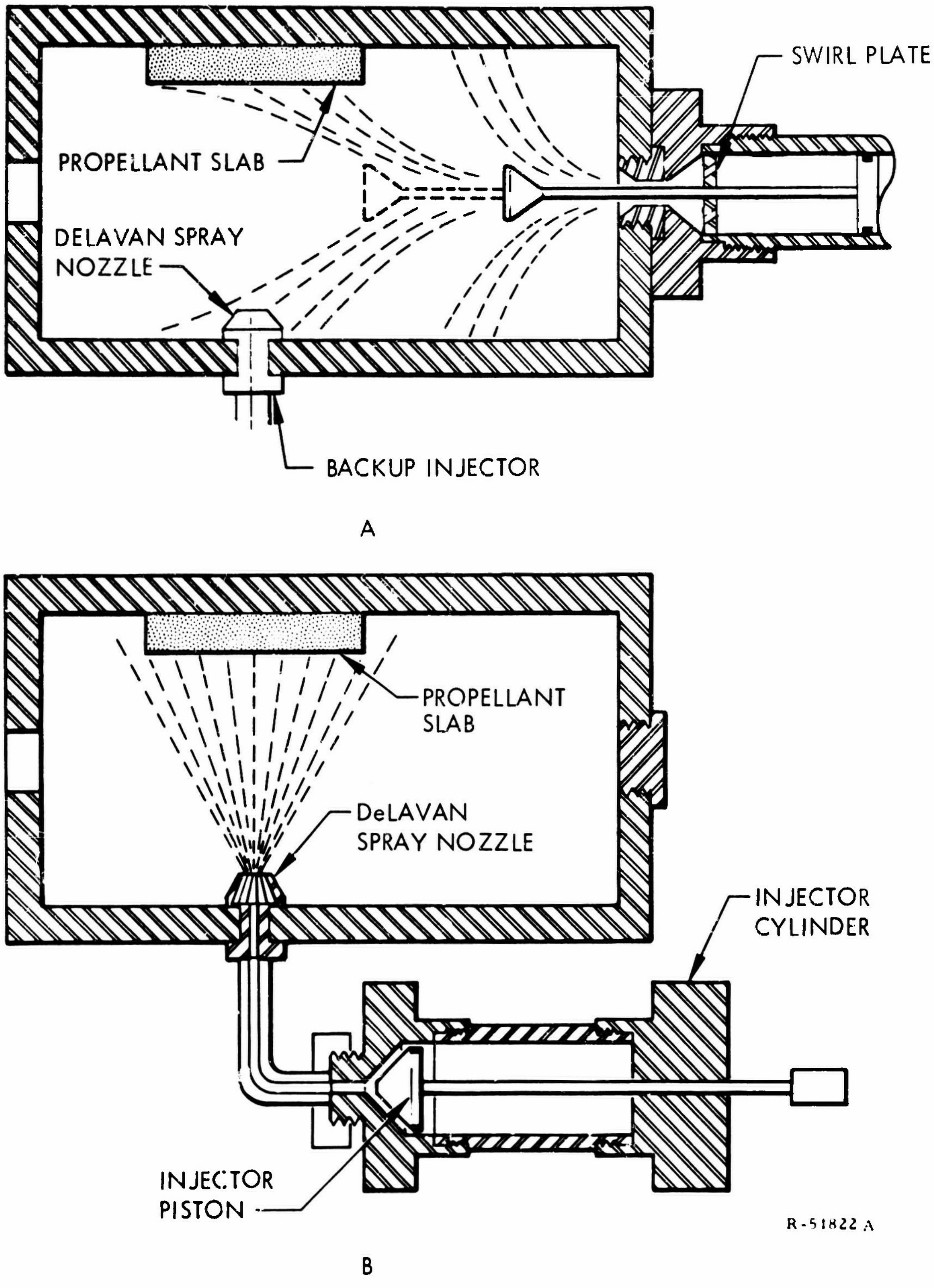

Figure 4. Two Basic Injector Nozzle Configurations Used in the Laboratory Motor

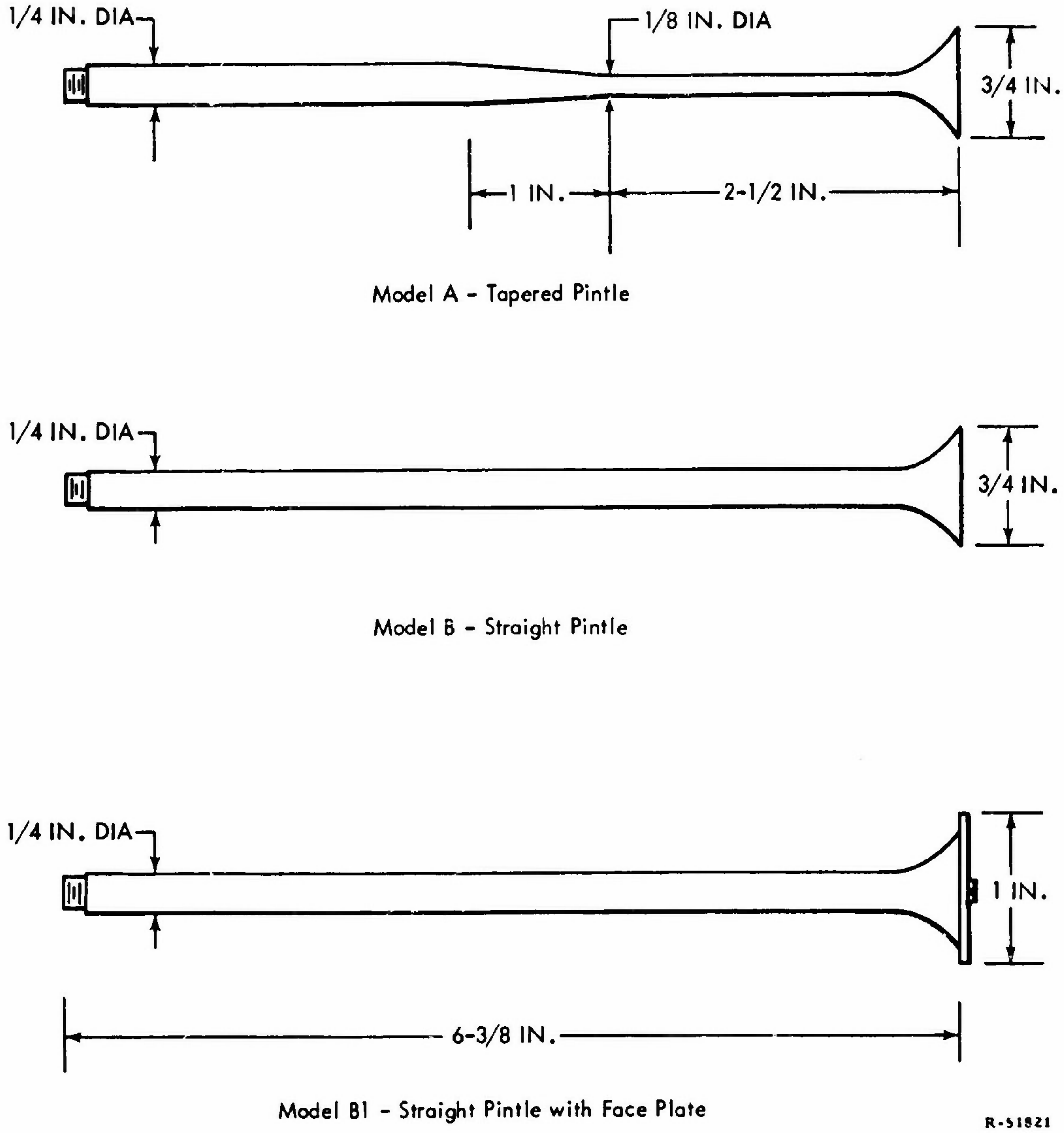

Figure 5. Laboratory Injector Pintle Configuration

of the injectant period than at the end. The straight shaft provided the same injectant flow throughout the injection period.

The third design was identical to the straight pintle except that a splashplate was attached to the face of the pintle to encourage injectant dispersion and improve the radial component of the injectant flow.

A backup injection system was used in all tests conducted with the pintle injectors. This system consisted of a water supply, pressurization system, and a commercial type spray nozzle mounted to provide a solid-cone spray directly only to the propellant surface. Previous testing at UTC had shown this to be a reliable method of extinguishing propellant combustion. The purpose of the backup system was to ensure extinguishment of the propellant in tests where the primary system had not provided complete extinguishment. Posttest examination of the unburned propellant would then allow evaluation of the primary injection system operation.

B. Spray Nozzles

Several types of commercially available Delavan* spray nozzles of the type shown in figure 4B were used. These nozzles were used in the solid-cone and solid-stream configurations.

3.1.1.2 Instrumentation

Test instrumentation included combustion chamber pressure, combustion chamber luminosity, injection piston position, and injector driving pressure. Data were recorded on a Consolidated Electronics Corp. (CEC), model 5-124, oscillograph recorder. Pertinent instrumentation data are presented in table II. High-response data acquisition systems were considered; however, analysis of the requirements (appendix I) indicated the above equipment to be adequate.

3.1.1.3 Test Program

3.1.1.3.1 Injector Evaluation Tests

Prior to the actual motor firings, a series of cold-flow tests was conducted to establish the injector flow characteristics. Initial cold-flow

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* Delavan Manufacturing Co., West Des Moines, Iowa, Catalog No. 33

TABLE II

LABORATORY INSTRUMENTATION DATA

Measurement	Range	Transducer	Accuracy %
Chamber pressure, psig	0-1,500	CEC type 4-326-0001	±0.50
Injection pressure, psig	0-2,000	Table model 206-Sa	±0.25
Injector piston position, in.	±3	G. L. Collins Corp. Linear Transducer, Model No. SS-109A	±0.5
Combustion luminosity	---	Silicon Photovoltaic Light Sensor Texas Instruments Inc., Model LS 223	---

tests were conducted with the tapered pintle (model A) injector in the special test fixture shown in figure 6. The objective of the tests was to determine the rate of sweep of water spray down the motor port as a function of injector pressure (pneumatic piston-driving pressure). Five flux gages were mounted along the inside of the test motor at equal intervals, the first being 1.5 in. downstream of the injector face. The injector, which was mounted at the head end of the motor, was filled with water. A total of 14 tests was conducted with the injection pressure varying from 50 to 500 psig. The tabulated test data are presented in table III.

In 9 of the 14 tests, the first sensor downstream of the injector failed to pick up on the proper sequence, indicating an erratic injection pattern and questionable coverage of the surfaces directly adjacent to the injector face.

To further evaluate the injection pattern, photographic studies of the tapered pintle injector were conducted. A Fastex camera with film speeds of 500 frames/sec was used. The injector pressure was varied from 100 to 500 psig. The total pintle translation time varied from approximately 65 msec at the highest pressure to more than 100 msec at the lowest pressure. Considerable pintle oscillation and irregularity of the spray pattern were noted. Tabulated test data are given in table IV.

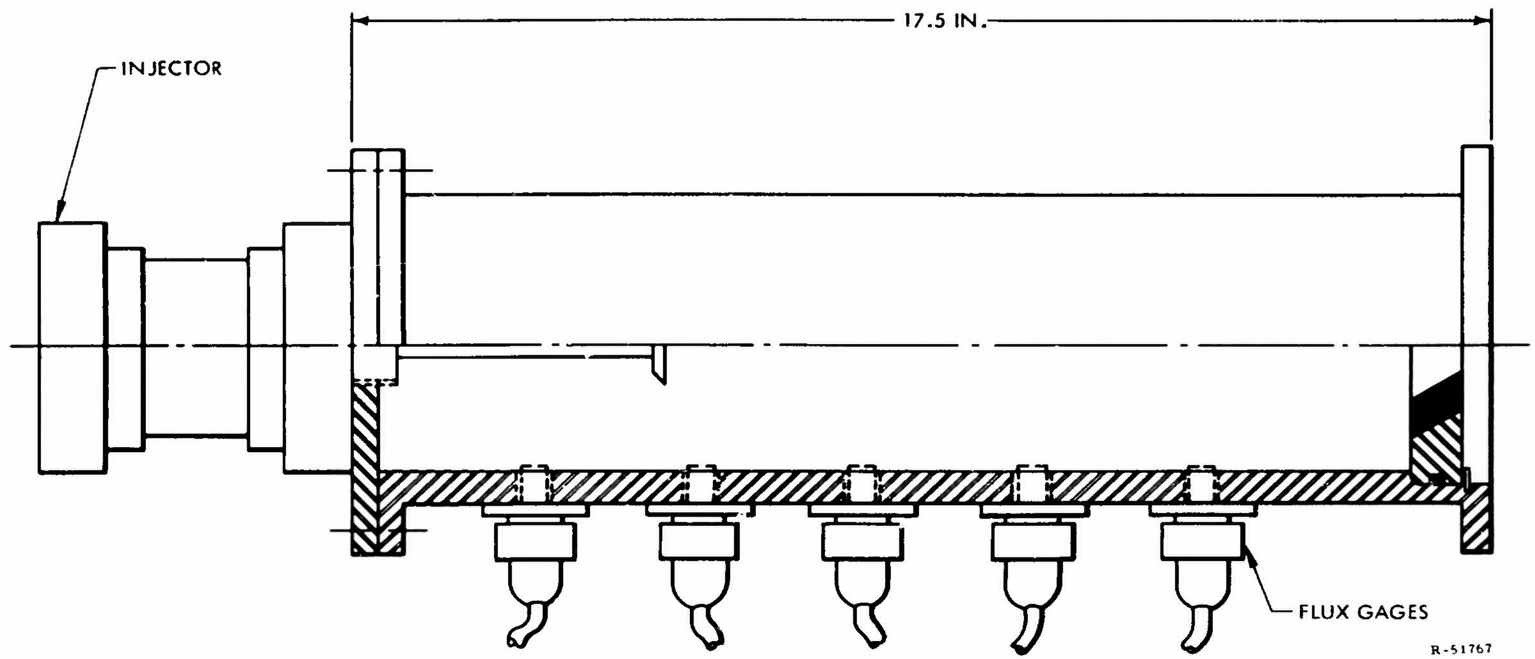


Figure 6. Ignition Propagation Motor

TABLE III

COLD-FLOW TEST RESULTS

Test No.	Injection Pressure, psig	Water Sweep Time, msec	Sensor Locations
1	200	95	Side position
2	200	110	
3*	300	100	
4	300	70	
5*	400	55	
6*	500	50	
7	50	220	
8*	100	210	Side position
9*	100	140	Top position
10*	100	125	
11	200	90	
12*	300	75	
13*	400	58	
14*	500	55	Top position

* Sensor No. 1 did not pick up in proper sequence

TABLE IV

PHOTOGRAPHIC INJECTION TEST

Test No.	Injection Pressure, psig	Approximate Pintle Translation Time, msec
1	200	81
2	200	65
3	300	64
4	400	58
5	500	59
6	100	100
7	150	71
8	250	65

In an effort to improve the radial spray pattern, a splashplate was attached to the end of the straight pintle, and an additional cold-flow test was conducted. A significant improvement resulting from the splashplate was noted in the radial component of the spray pattern.

Four laboratory motor firings were then conducted for injector development.

The first motor firing was conducted with the tapered pintle (model A) injector and the propellant tray mounted toward the forward end of the motor. (The propellant molds may be located either toward the forward or aft end of the motor.)

The injector for the primary system was charged with 0.071 lb of water to provide a spray density of 0.0063 lb (H_2O)/in.^{2} of propellant surface, which was in excess of the requirements reported by Aerojet-General Corp.[2] and Allegany Ballistics Laboratory (ABL).[3] The injection pressure was set at 600 psi, providing an injectant flow rate of 1.42 lb/sec and an injection time of 0.060 sec.

Data obtained included motor chamber pressure and combustion luminosity (with light sensor). The termination sequence was initiated satisfactorily, but combustion over the entire propellant surface was not extinguished. Chamber pressure dropped to a minimum of 60 psig, where it remained until burnout. The secondary injection system was used, but the time delay prior to its initiation was such that it coincided with burnout. A possible cause of the incomplete termination was that the propellant was positioned too far forward in the motor and that the forward end of the propellant slab was not contacted by injectant.

The second firing was conducted with the same injector configuration, charge weight and flow rate, but the propellant was positioned toward the aft end of the motor so that the injection pattern would cover the entire propellant surface. Extinguishment appeared to have been achieved upon water injection, but the propellant began to reignite, as evidenced by smoke emitted from the motor nozzle. The secondary injection system was initiated, resulting in permanent extinguishment. Postfire examination of the propellant grain indicated that the primary injection system had extinguished combustion over all of the propellant surface except for two small areas which were protected from direct water impingement by the lip of the propellant mold (see figures 7 and 8). The maximum chamber pressure decay rate during extinguishment with the primary injection system was 13,000 psi/sec. Because this is an order ot magnitude lower than that required to terminate combustion as a result of pressure drop (dp/dt) alone, it was concluded that in order to extinguish combustion in a motor by fluid injection, the fluid must make contact with the entire burning surface.

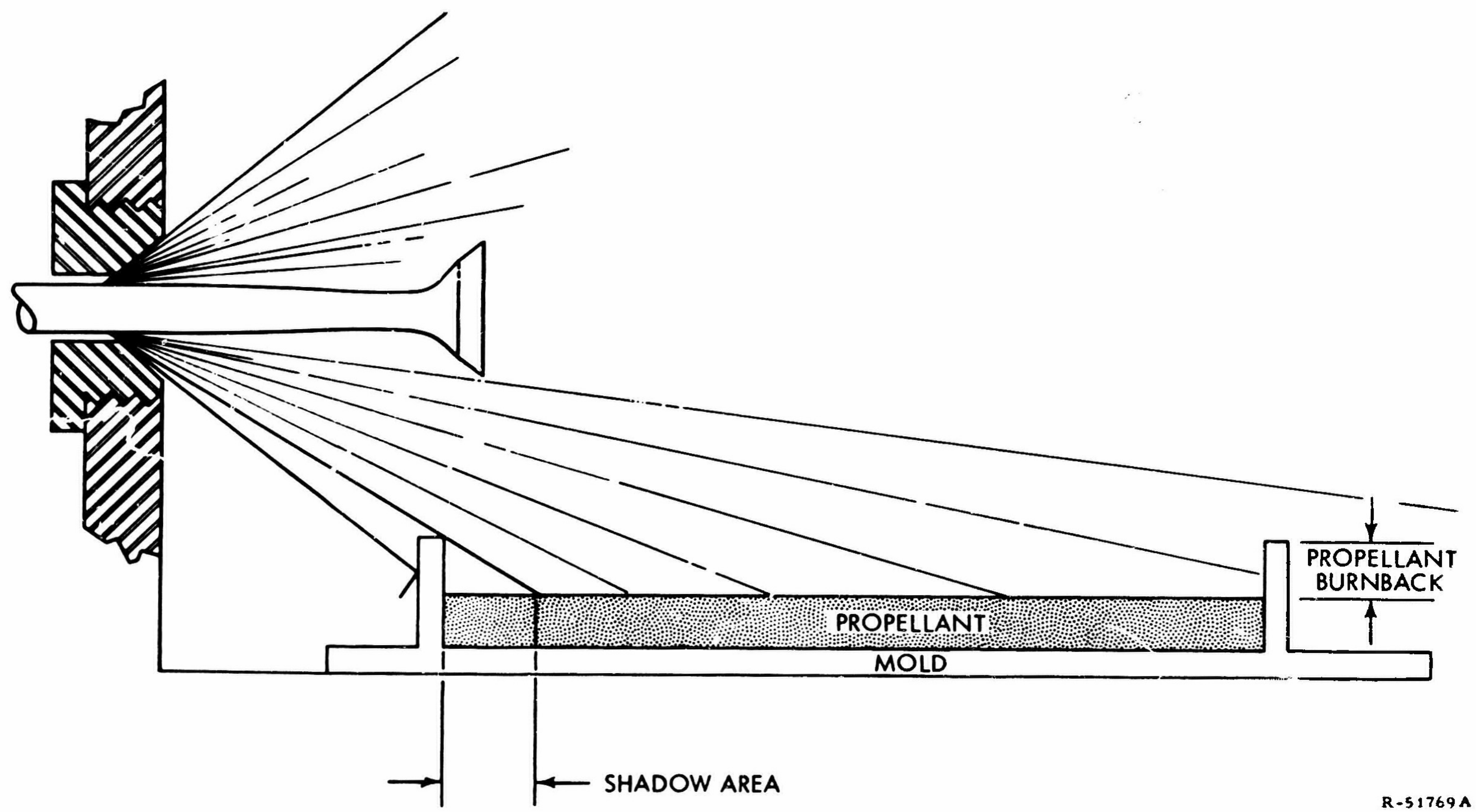


Figure 7. Propellant Mold in Laboratory Motor
Showing Shadowed Area

Figure 8. Propellant and Propellant Mold Showing Areas Not Extinguished by the Primary Injector

The third test was conducted with the same charge weight and flow rate but with a straight pintle (model B) which was expected to provide a higher initial velocity component in the radial direction, thus providing complete coverage of the propellant surface. The propellant was again positioned toward the aft end of the motor. The primary injection system again failed to completely extinguish combustion, and the secondary system was successfully used. Posttest examination of the propellant grain revealed that the portion of the grain along the back of the propellant mold had again failed to be extinguished by the primary injector. The chamber pressure instrumentation was inoperative on this test.

The fourth test was conducted with a straight pintle which had a 1-in.-diameter splashplate attached to the face (model B1). The expected dispersing action of this injector is shown on figure 9. The injector charge weight was the same as the previous test, but the injection pressure was set at 450 psig, which resulted in a slightly lower flow rate. The primary injection system completely extinguished all combustion in this test. The maximum motor chamber pressure decay rate was 3,150 psig/sec.

The injection system utilizing a positive displacement piston proved to be an excellent development tool.

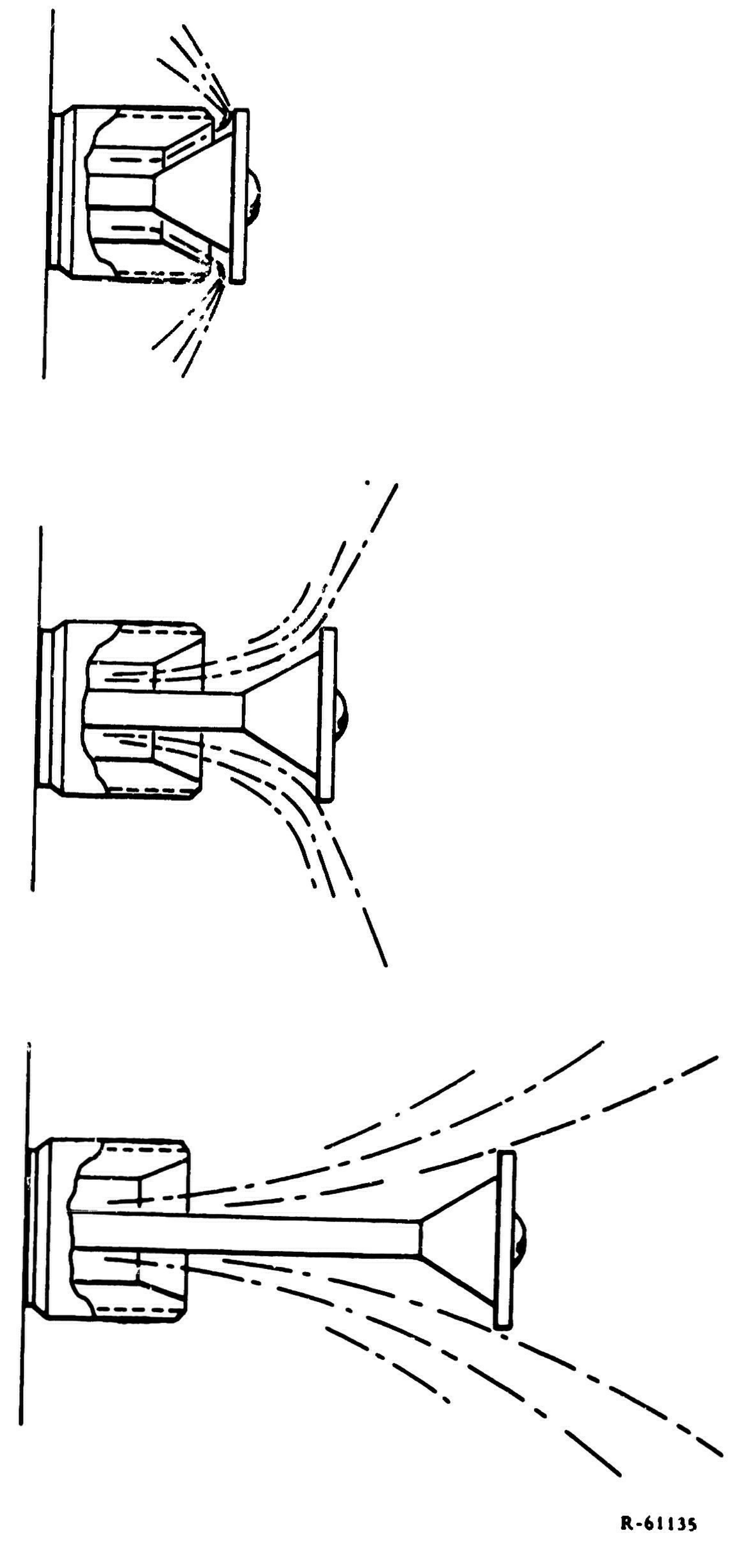


Figure 9. Expected Dispersion Pattern of Straight Pintle Injector

The two important injection variables, charge weight and flow rate, were found to be easily and accurately monitored with this system. In addition, the use of a piston to expel the injectant served to close the forward end of the motor and prevent the backflow of hot gases into the injector when reignition did occur.

3.1.1.3.2 Injectant Evaluation Tests

Injectant evaluation tests were conducted to determine the relative effectiveness of several candidate injectant fluids in terminating combustion. The results of these tests are presented in table I. In these tests, the injector shown in figure 4B was used. The Delavan nozzles used with this injector normally provide a solid-cone spray pattern; however, in several tests the swirl plate in the nozzle was removed to provide the solid stream shown in figure 10.

Injectants which were evaluated included: (1) water, (2) water containing surface active agents, (3) water containing a suspension of carbon black, (4) water and ammonium bromide, (5) Freon 114B-2, and (5) N_2O_4. The primary consideration in selection of injectants was heat capacity. However, Freon and N_2O_4 were investigated on the basis of their ready availability in most test stands and flight systems. A summary of important injectant data is presented in table V, and the test results are summarized in table I. For purposes of evaluation, each candidate was compared to water.

All tests were conducted at chamber pressures varying from 390 to 490 psig. Test data included motor chamber pressure, propellant combustion luminosity, injector piston movement (injectant flow rate), and injection pressure. Typical pressure versus time curves showing both termination and reignition are shown in figures 11 and 12.

Two calibration tests (No. 005 and 006) using water as the injectant were conducted to check out the modified system and to define baseline requirements for flow rate and total injectant quantity.

While complete extinguishment was not accomplished on either test, the pressure versus time transient from test No. 6 indicated that extinguishment had been nearly accomplished and that the flow parameters used in this test were near the minimum required for extinguishment.

The first two injectant evaluation tests (No. 007 and 008) were conducted with water containing commercial surface active agents. Injection parameters just below those established in tests No. 005 and 006 were used. In this manner, an improvement over water as an injectant would

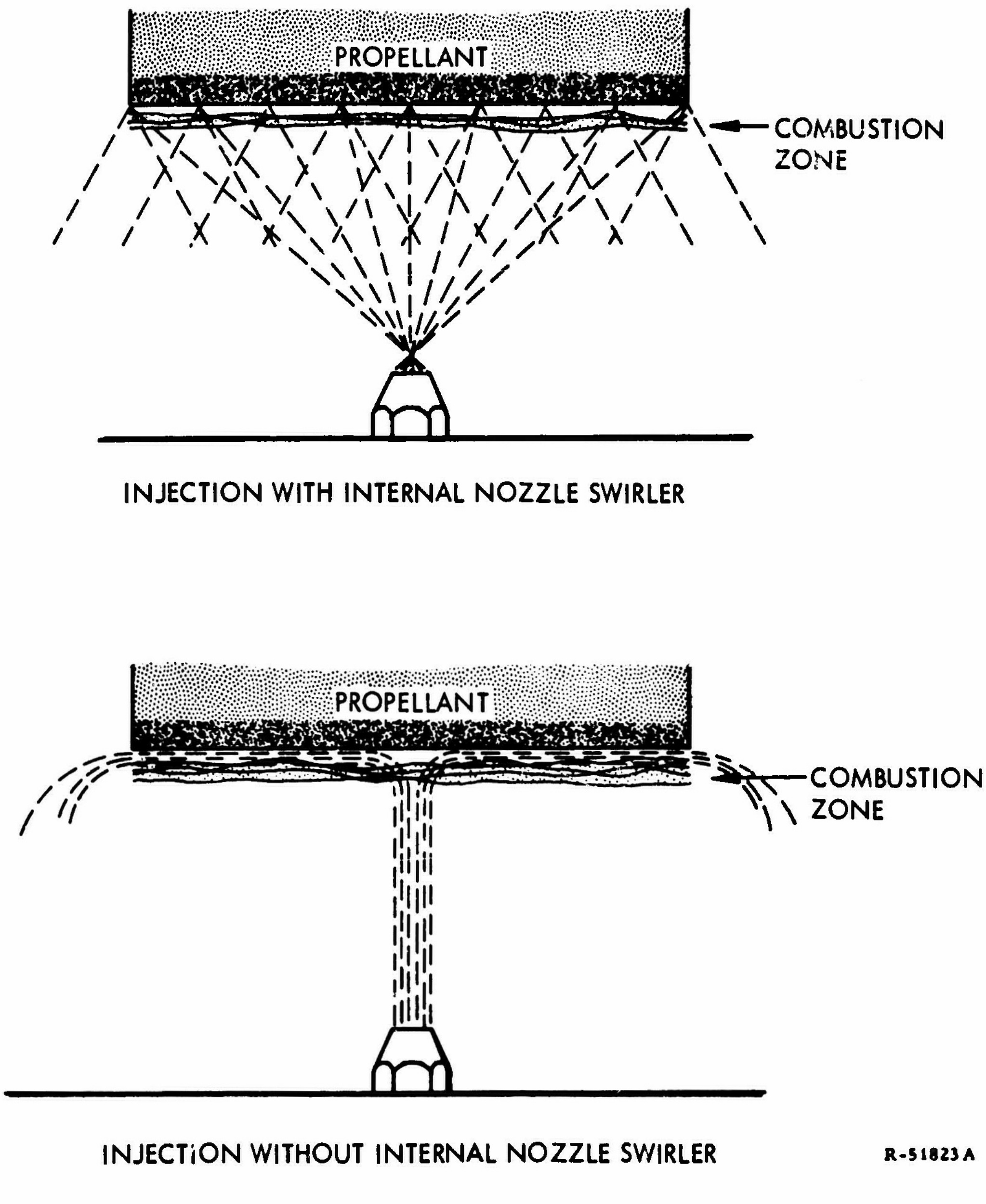


Figure 10. Injection Patterns for Injector Positioned Opposite the Propellant Grain Surface

TABLE V

INJECTANT DATA

Injectant	Concentration % Weight in Water	Specific Gravity (at 70° F)	Bulk Specific Heat of Vaporization (Btu/lb)	Bu Capac (Bt
Freon 114 B-2 ($CBrF_2$ - $CBrF_2$)	100	2.16	45 (est)	
Nitrogen tetroxide (N_2O_4)	100	1.45	171	
Water/ammonium bromide (H_2O/NH_4Br)	41.2	1.27	573 **, †	
Liquiblack (Water/carbon black and surfactant)	26	1.14	720 †	
Water/Sterox NJ (ethoxylated nonyl phenol type surface active agent)	2	1.0 †	973 †	
Water/Santomerse No. 1 (40% dodecylbenzene plus 60% sodium sulfate)	2	1.0 †	973 †	

* Approximate values for atmospheric pressure.

** NH_4Br sublimes endothermically at 754° F with heat of sublimation of 745 Btu/lb.

† Amount contributed by water only.

A

ABLE V

DATA SUMMARY*

Bulk Heat Capacity-Liquid (Btu/lb° F)	Specific Heat Vapor (Btu/lb° F)	Total Enthalpy Ratio $\Delta H_{inj}/\Delta H_{water}$ (68° to 5500° F)	Supplier
0.166	0.15 (est)	0.24	E. I. Du Pont De Nemours & Co.
---	0.096	0.20	
0.688	0.392	0.76	Mallinckrodt Chemical Works
0.844	0.452	0.90	Concrete Chemical Co. Redwood City, California
1.0†	0.47†	1.00†	Monsanto Chemical Co.
1.0†	0.47†	1.00†	Monsanto Chemical Co.

ı/lb.

B

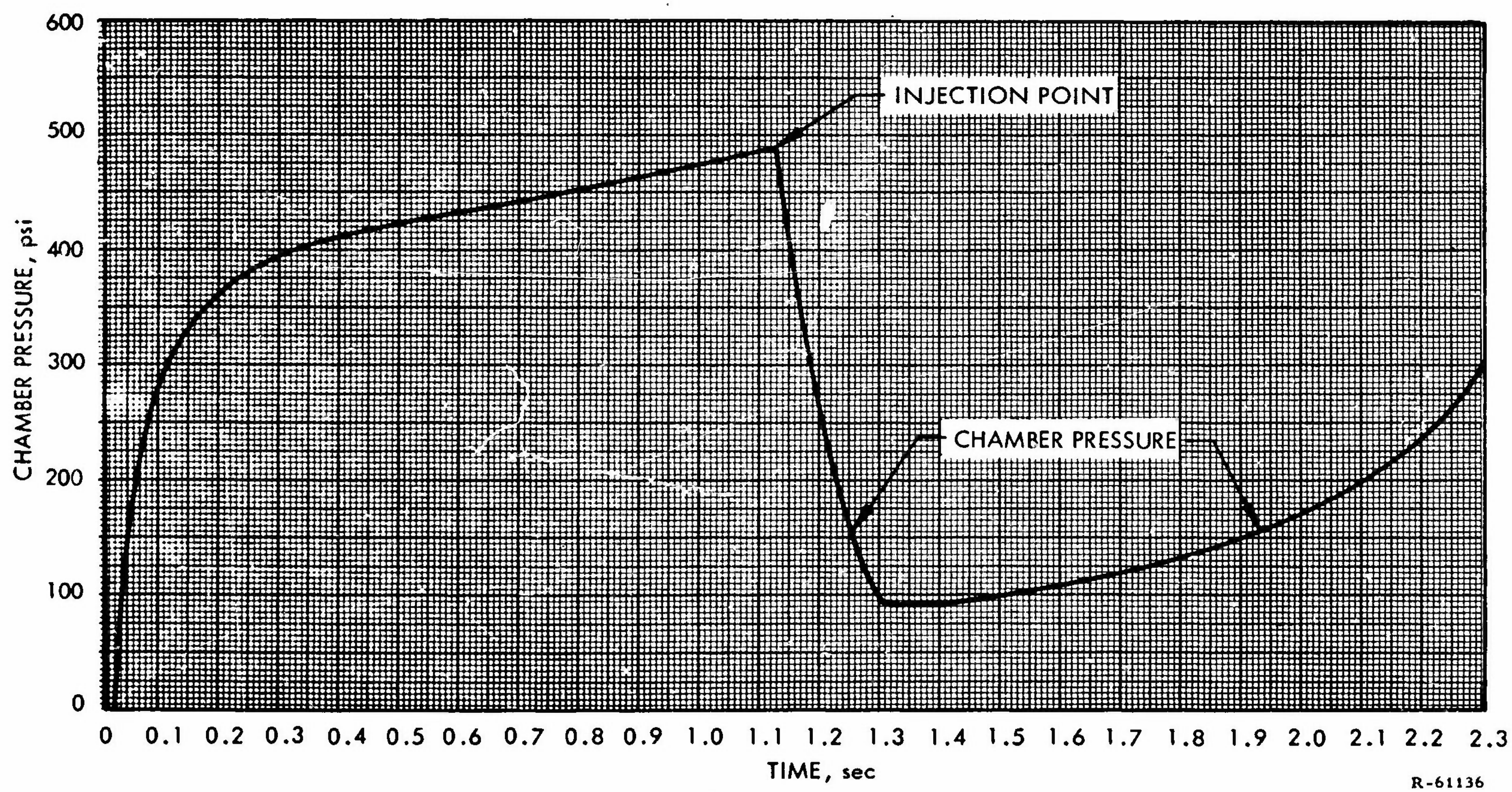


Figure 11. Chamber Pressure vs Time, Laboratory Test No. 006 (Reignition)

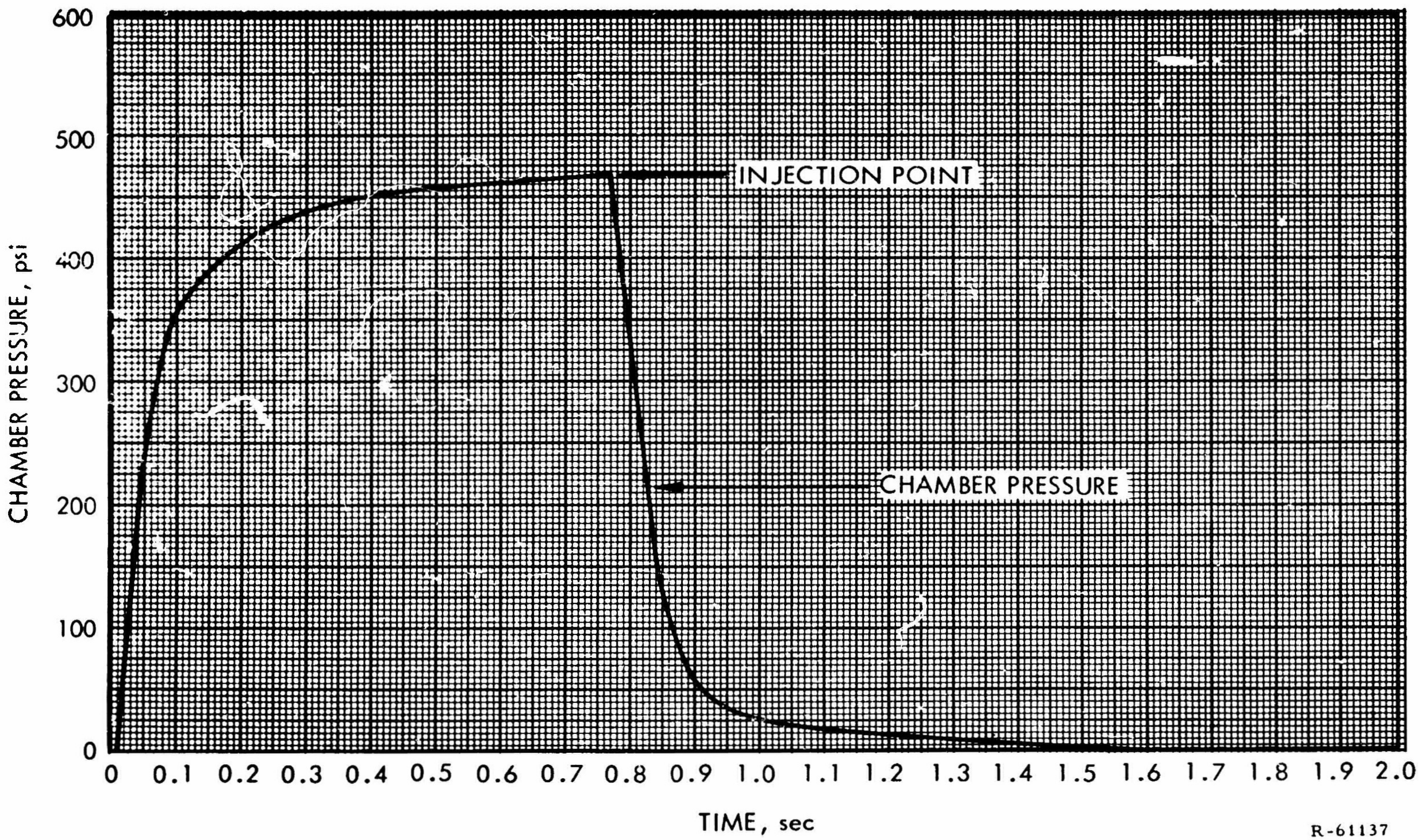


Figure 12. Chamber Pressure vs Time, Laboratory Test No. 007, (Termination)

be evident if a positive extinguishment occurred. Although combustion was interrupted in both tests, the propellant reignited. Test No. 009, which used untreated water as the injectant, also failed to extinguish combustion completely. However, injection parameters were lower than expected because the swirl plate in the Delavan nozzle had apparently been damaged by the ingestion of hot combustion gases when the motor reignited during the previous tests.

Test No. 010, which used a solution of 10 parts water to 7 parts ammonium bromide (by weight), also failed to completely terminate combustion, although the critical flow parameters were considerably above those established for water extinguishment.

In test No. 011, which used Freon 114B-2 as the injectant, a significant motor overpressure occurred (see figure 13). Within 12 msec after injection initiation, combustion chamber pressure increased from a steady-state value of 490 psig to 645 psig, at which point a safety burst disk ruptured, venting the chamber to the atmosphere. As shown in table I, the injection parameters for this test were considerably higher than those required for water termination.

A suspension of commercially available carbon black in water (26% carbon by weight) was used in test No. 012. This test also failed to achieve complete combustion termination.

Tests No. 013, 014, and 015 were conducted using N_2O_4 as the injectant. Test No. 013 failed to terminate combustion and resulted in a motor overpressurization which ruptured the safety burst disk. However, no data were obtained because of an instrumentation failure.

Test No. 014 was aborted before motor ignition because of a failure in the test sequencer. Test No. 015 failed to terminate combustion, and as in test No. 013, the safety burst disk ruptured because of motor overpressurization.

Test data shown in figure 14 indicate that an increase in motor chamber pressure from a steady-state value of 455 psig to 690 psig within 12 msec was followed by motor depressurization upon rupture of the safety burst disk. Coincident with the rise in chamber pressure, an increase in intensity of the combustion luminosity was observed. This was probably caused by second order combustion of the injectant with the solid propellant combustion products.

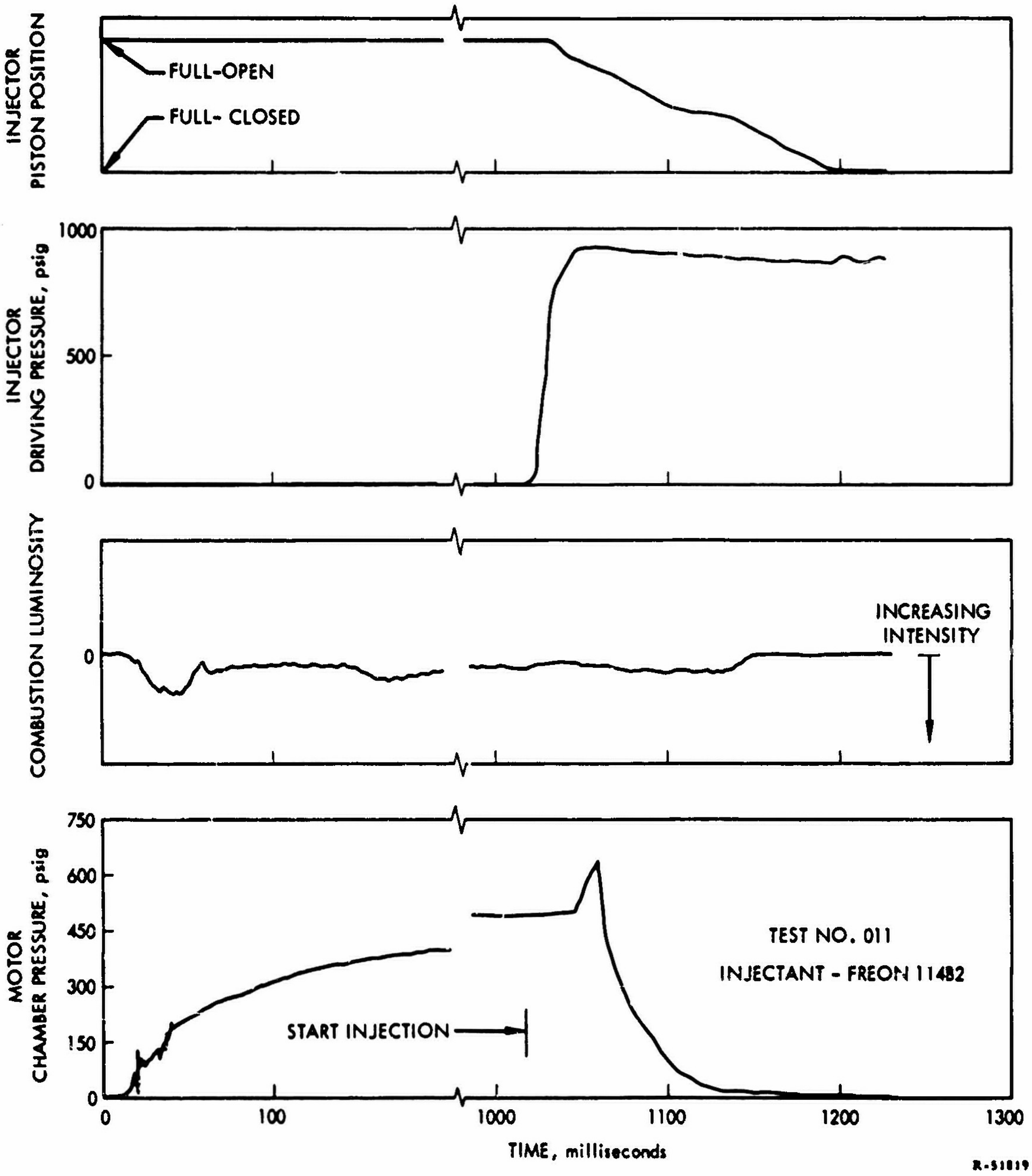


Figure 13. Test Data for Freon 114B-2 Injection

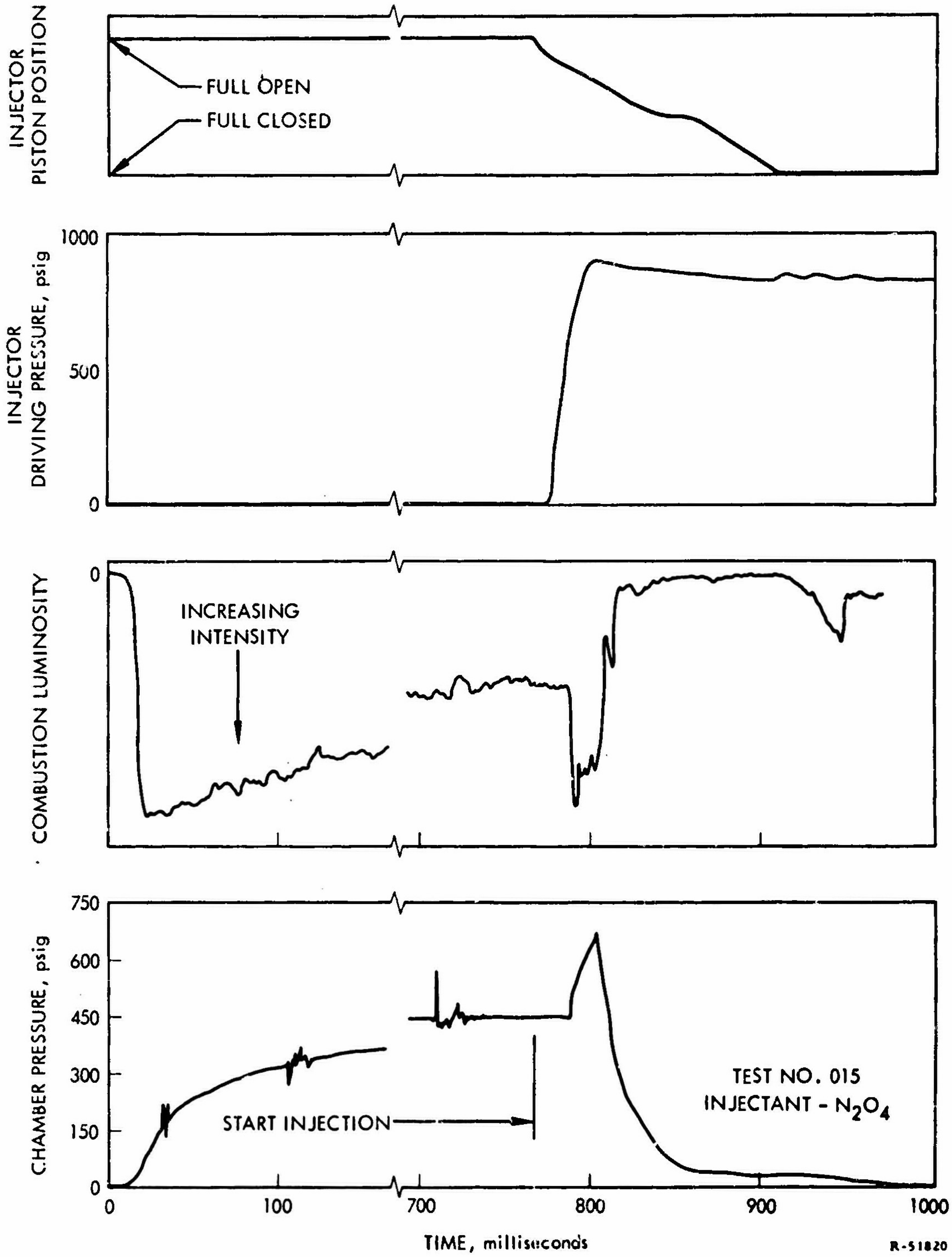


Figure 14. Test Data for N_2O_4 Injection

Tests No. 016 through 020 were conducted to verify critical water injection parameters for the laboratory combustion termination motors. Earlier tests had indicated a shift in the critical parameter line. Specifically, the tests were to investigate causes of this shift and to verify that injection evaluation was being conducted with parameters which were in the same range as required for combustion termination with water.

Tests No. 021 through 024 were conducted to reevaluate water containing a surface active agent in view of the corrected baseline requirements established in tests No. 016 through 020.

3.1.1.4 Test Results

The injector evaluation tests, both cold-flow and motor extinguishment, established the pintle injector as a satisfactory means of dispersing the injectant onto the solid propellant grain.

Some problem in achieving radial dispersion was noted in the cold-flow tests. This resulted from the forward angle of the sealing surfaces between the pintle and injector barrel which directed the water forward. The incorporation of a splashplate to the face of the pintle improved the radial dispersion of the water.

The injectant survey tests indicated that the water with surface active agents added may provide some advantage over plain water as the injectant. However, improvement was not significant. The solutions of carbon black and water and ammonium bromide and water did not increase the effectiveness of water, and serious motor overpressurizations were noted on tests using Freon 114B-2 and N_2O_4 as injectants. These overpressures could be predicted on the basis of analytical work previously conducted at UTC (see appendix II).

At the completion of the N_2O_4 tests, an attempt was made to verify the baseline requirements established in tests No. 005 and 006. Test No. 016 was conducted for this purpose, and although the flow parameters were significantly above the baseline requirements, complete extinguishment was not achieved. In an effort to improve the effectiveness of the injector and thereby provide extinguishment, the internal swirl plate was removed from the Delavan nozzle so that the injectant impinged on the propellant surface in a solid stream. Tests No. 17 through 20 were then conducted, and baseline injection requirements were established for water. The results of earlier tests comparing water/surface active agent solutions were now invalid because the new baseline requirements differed from those established in tests No. 005 and 006. Therefore, tests No. 021 through 024 using a solution of water and sterox were conducted. These tests

indicated a possible reduction in critical injection parameters over those required for water only. While the improvement was not significant in the laboratory motor, it may increase for larger-scale motors and may also increase the probability of complete extinguishment because of the increased wetting action of the mixture.

3.1.2 Small Motor (TM-1) Tests

Twenty-four TM-1 motor tests were conducted to investigate various candidate injectors and to establish flow parameters required for the design of the TM-3 motor injection system.

3.1.2.1 Test Hardware Description

3.1.2.1.1 Motor Description

The small motor test program was based on the use of the standard UTC TM-1 test motor (shown in figure 15) which is used extensively for both development testing and propellant batch analysis. The motor consisted of a heavy-duty steel chamber, a steel aft closure with a graphite nozzle insert, and a cartridge-loaded, cylindrical-port solid propellant grain. A pyrotechnic pellet bag containing boron potassium nitrate ($BKNO_3$) pellets and an electric squib was used for ignition. The predicted pressure transient for the motor is shown in figure 16.

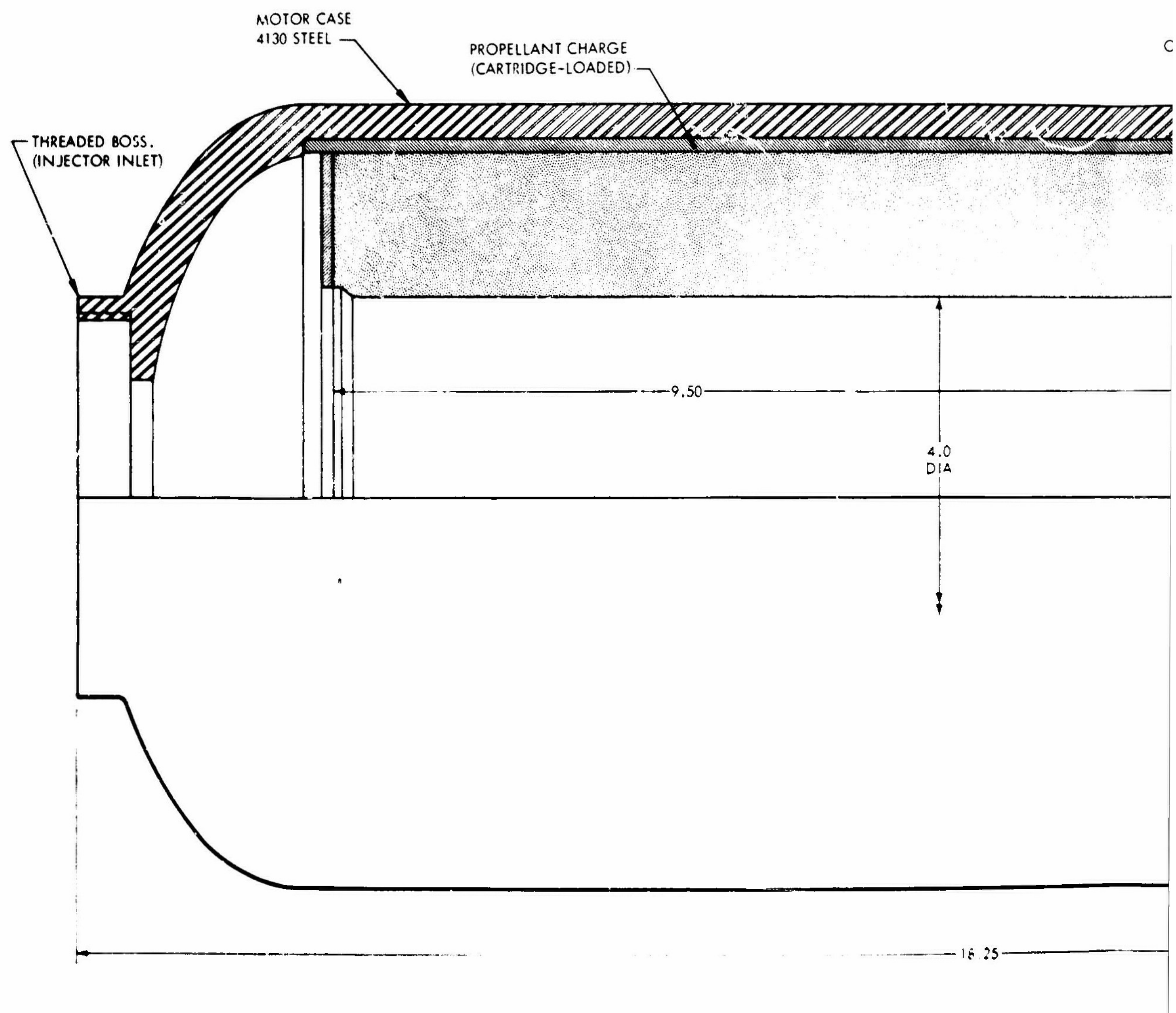
For this test series, two basic TM-1 motor configurations (designated -03 and -04) were tested.

In the -03 configuration, which was used for the first 14 firings, both ends of the 15-lb UTP-3001 propellant grain were inhibited. This resulted in an internal-burning cylinder, which was used as a standard for the evaluation of various injectors.

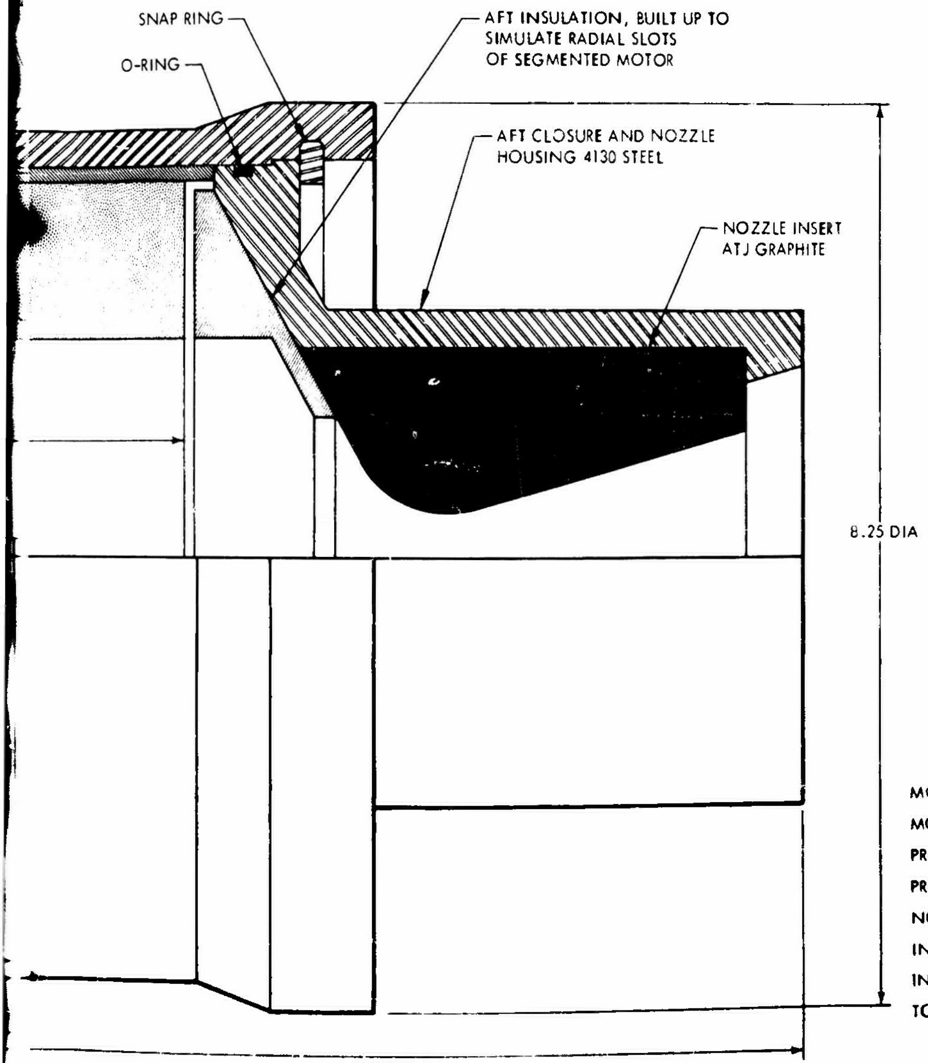
The -04 configuration utilized a forward-end inhibitor only. The aft face of the grain was allowed to burn in order to geometrically simulate a typical radial slot between the segments of a segmented motor. To increase the similiarity, insulation was built up on the aft closure to simulate the subsequent segment and provide a complete slot configuration. This motor configuration utilized a smaller nozzle to obtain data at higher chamber pressures.

3.1.2.1.2 Injection System Description

The injection system, shown in figure 17 with the piccolo injector, consisted of a heavy steel cylinder, two end closures, and a piston. As in the laboratory motor injector, the charge weight was controlled


MOTOR CASE
4130 STEEL
PROPELLANT CHARGE
(CARTRIDGE-LOADED)
THREADED BOSS.
(INJECTOR INLET)
9.50
4.0
DIA
18.25

11



TM-1 TEST MOTOR

MOTOR LENGTH, in.	18.25
MOTOR DIAMETER, in.	8.25
PROPELLANT WEIGHT, lb	14.4
PROPELLANT CHARGE CONFIGURATION	CYLINDRICAL PORT
NOZZLE THROAT DIAMETER, in.	1.13
INITIAL PROPELLANT SURFACE AREA, in^2	148
INITIAL MASS FLOW RATE, lb/sec	3.3
TOTAL IMPULSE, lb-sec	3540

R-61138

B

Figure 15. Standard UTC TM-1 Test Motor

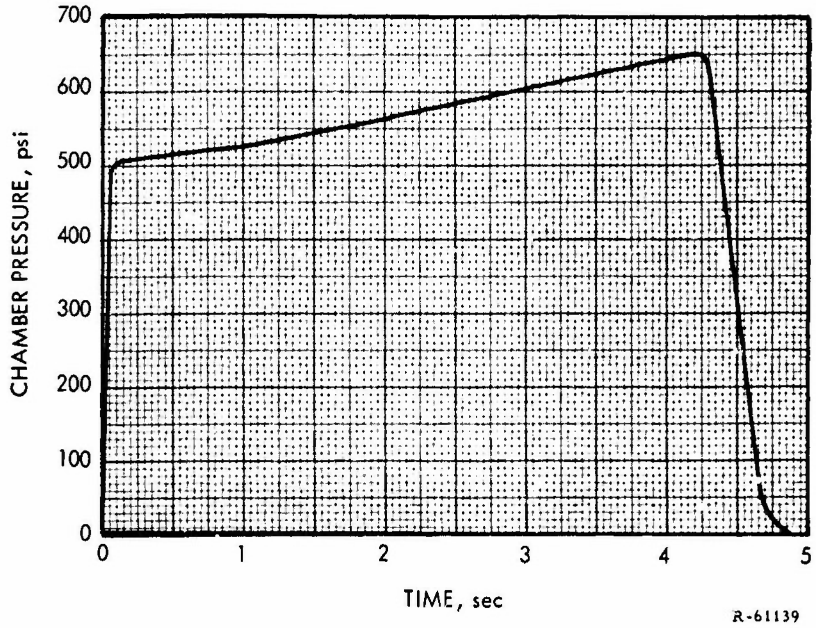


Figure 16. Predicted Pressure vs Time Transient, TM-1 Motor

by the driving pressure. The forward end of the injector mates with the threaded opening at the forward end of the TM-1 motor and is adaptable to a variety of injector types. The volume in front of the piston is filled with water from one of the two fittings on the forward end, and the other fitting is used to monitor injection pressure.

The injector piston is driven by GN_2 supplied by a high-pressure ullage tank mounted behind the injection assembly. Two burst disk assemblies and a bleed valve are used to provide high pressurization rates. A schematic of the test setup is presented in figure 18. The operating cycle is as follows:

A. The bleedline solenoid valve is closed and the other two solenoid valves are opened. The pressure regulator is then opened, charging both the accumulator and the space between the burst diaphragm assemblies to 600 to 700 psig.

   The upstream burst diaphragm assembly is rated at 1,800 psig, and the one next to the motor is rated at 800 psig. The solenoid valve spanning the first burst diaphragm is then closed, and the accumulator is brought up to the full operating pressure of 2,000 psig.

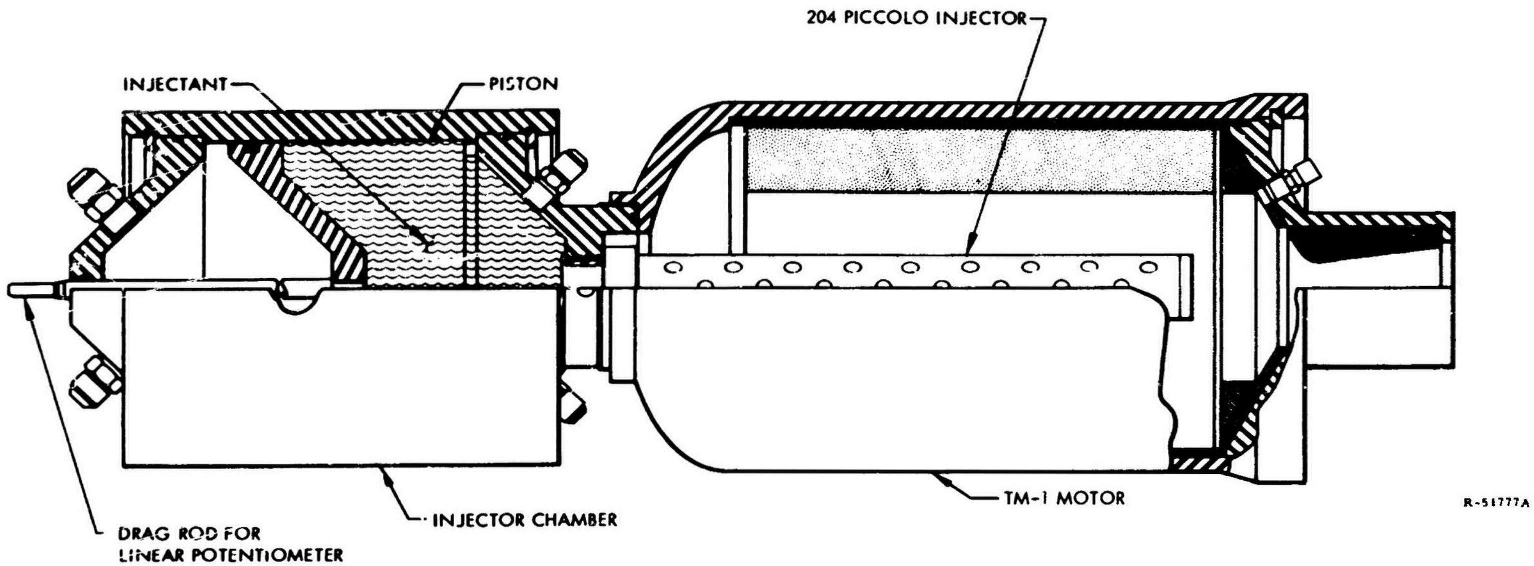


Figure 17. Injector Installation

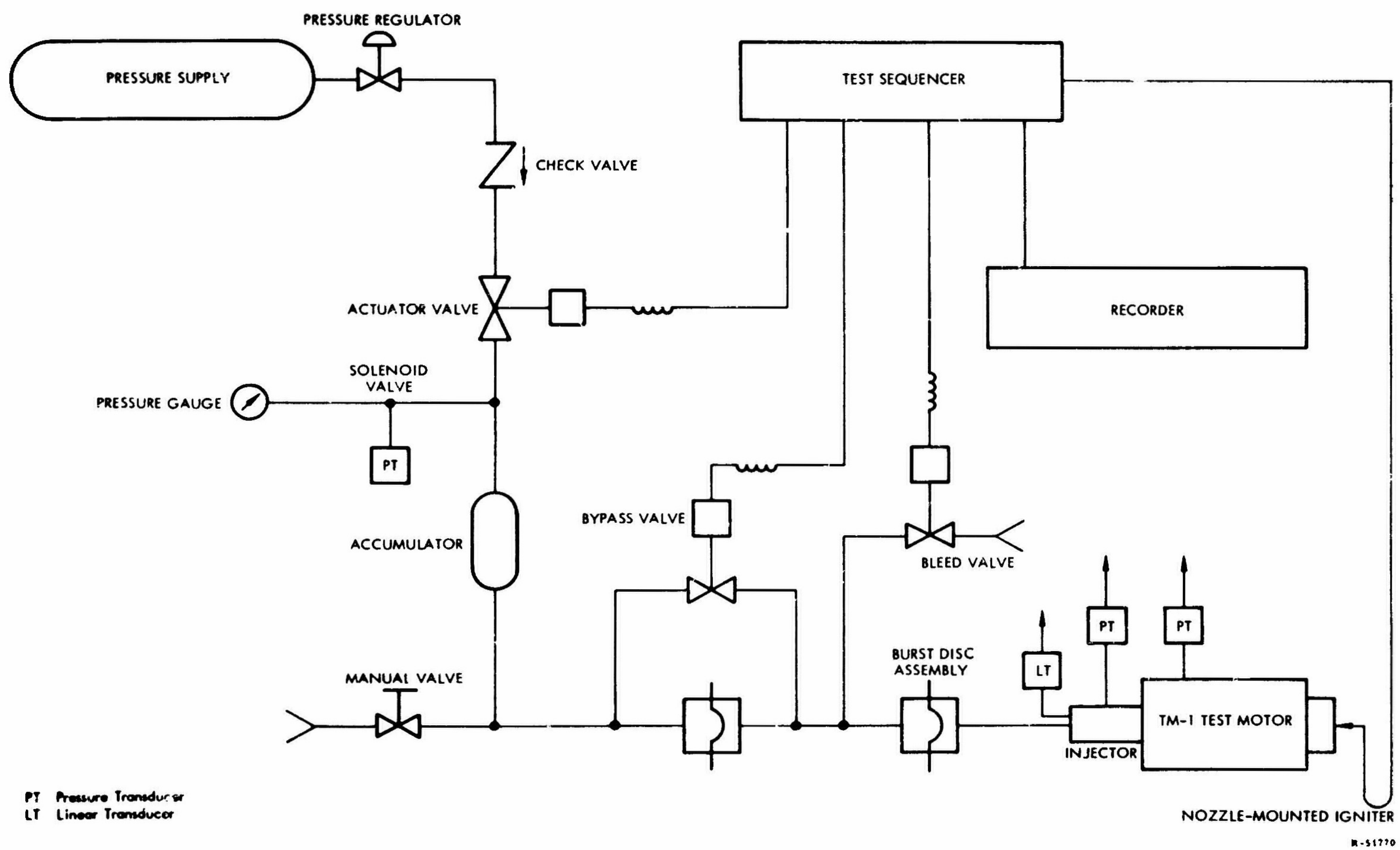


Figure 18. Test Setup for TM-1 Combustion Termination Test

B. The injection system is actuated by energizing the bleedline solenoid valve. The venting of this chamber ruptures the upstream burst diaphragm, and the rapidly moving gas overpressurizes the second burst diaphragm, producing an extremely rapid pressurization of the injector assembly. The transducers provide a pressure-time history of the injector and motor chamber pressure. These transducers, in conjunction with the light sensor, indicate time of propellant extinguishment.

The piston is provided with a drag rod which extends through the aft closure. The drag rod is attached to a linear transducer to allow monitoring of the piston position in relation to time. The piston also prevents backflow in the event of reignition of the propellant grain. Figure 19 shows the injection system and motor ready for testing.

3.1.2.1.3 Injectors

Five injector configurations were tested. Three of these injectors (designated 201, 202, and 203) were various types of commercially available spray nozzles which provided either solid- or hollow-cone sprays. The 204 configuration is a piccolo injector, and the 205 and 206 configurations are versions of the pintle design. Injector data are presented in table VI, and basic injector configurations are shown in figure 20.

All of the injectors except the 205 configuration were evaluated in at least one motor firing. This configuration is the same as the 206 configuration without the splashplate on the pintle face. As discussed in section 3.1.1.3.1, laboratory tests indicated that a splashplate was desirable.

3.1.2.2 Instrumentation

Each test was instrumented to record motor pressure, GN_2 pressure, injectant pressure, and piston movement. All pressures were measured with Taber 206 pressure transducers. Originally, it was anticipated that the pressure decay rate (dp/dt) would require the use of a higher response transducer. However, analysis indicated that a strain gage type (Taber) transducer was satisfactory. Piston movement, from which both injectant quantity and flow rate are obtained, was monitored with a G. L. Collins, model SS-109A, linear transducers. This unit is accurate to within ±0.5%.

All data were recorded on a CEC oscillograph.

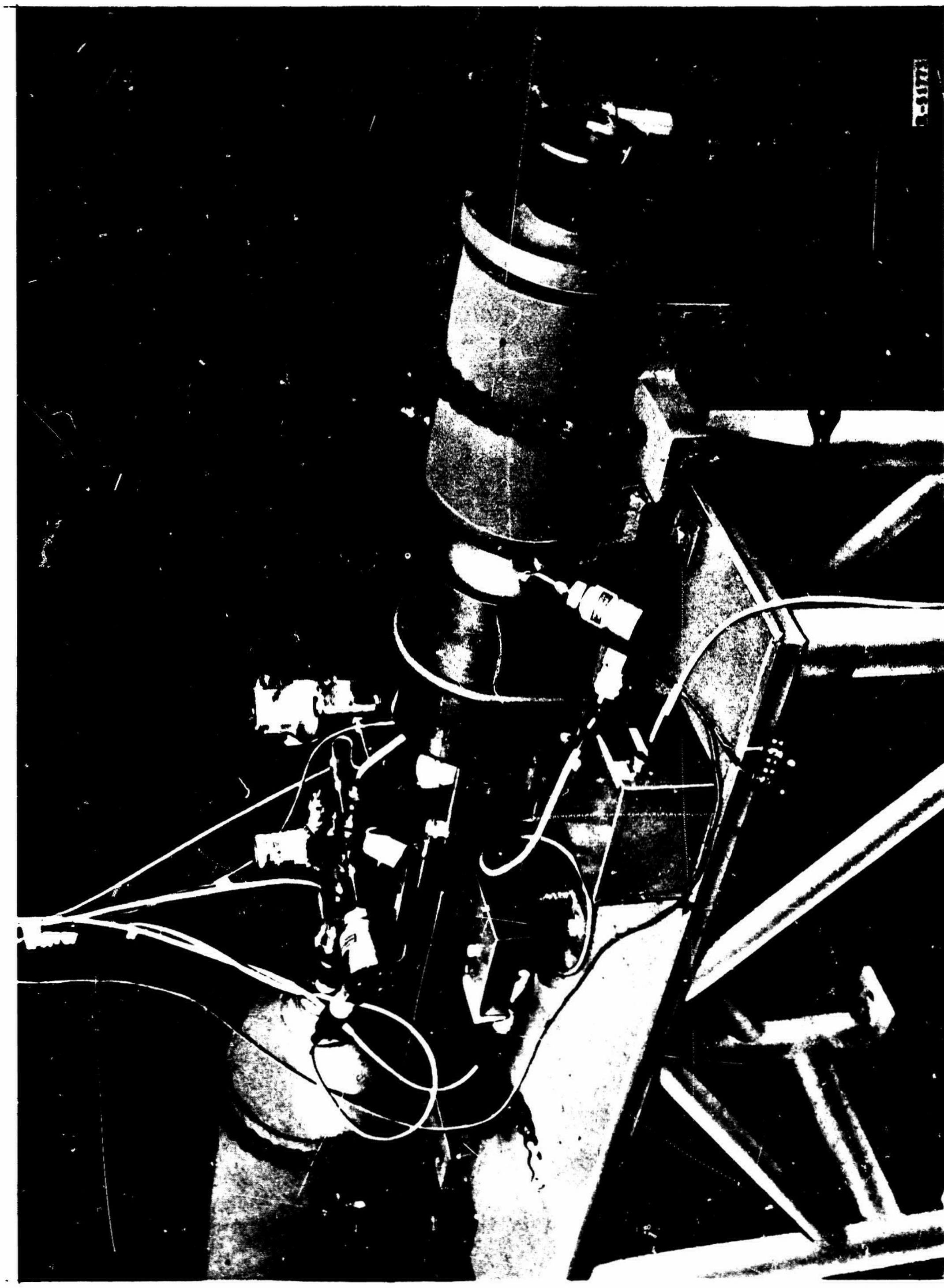


Figure 19. TM-1 Test Configuration

TABLE VI

TM-1 INJECTOR DATA

Injector	Type	Spray Pattern	Manufacturer
201	Conventional single orifice	95° Full cone	Steinen SSM 2608 (26 gpm at ΔP = 40)
202	Conventional single orifice	75° Hollow cone	Delavan 3/4-WSM-SS-100-75 (10 gpm at ΔP = 40)
203	Conventional single orifice	75° Full cone	Delavan 3/4-SCM-150 (15 gpm at ΔP = 40)
204	Piccolo	Radial	United Technology Center
205	Moving pintle	Progressive	United Technology Center
206	Moving pintle	Progressive	United Technology Center

3.1.2.3 Test Program

Using 5 of the 6 injectors, a total of 24 tests was conducted. Three tests were conducted with the 201 injector, four tests with the 202 injector, six tests with the 203 injector, six tests with the 204 injector, and five tests with the 206 injector. The tabulated results of these tests are presented in table VII. Combustion termination of the solid propellant grain was accomplished in the first firing, thus providing a data point for selection of the test parameters for subsequent tests.

The purpose of these tests was to establish a relationship between the various injector properties (mass flow, total water, and water velocity) and the physical and ballistic properties of the test motor. Complete extinguishment of the grain after fluid injection occurred in 15 tests. One test (test No. 7 in table VII) resulted in continuous burning throughout the injection time. A typical TM-1 combustion termination firing is shown in figure 21. Typical pressure-time curves are shown in figures 22 and 23.

During testing it was necessary to provide a positive means of retaining water in the injection chamber until the injection phase was initiated. This was accomplished by fitting a small burst diaphragm over the orifice of the 201, 202, and 203 injectors. The 206 injector provides a

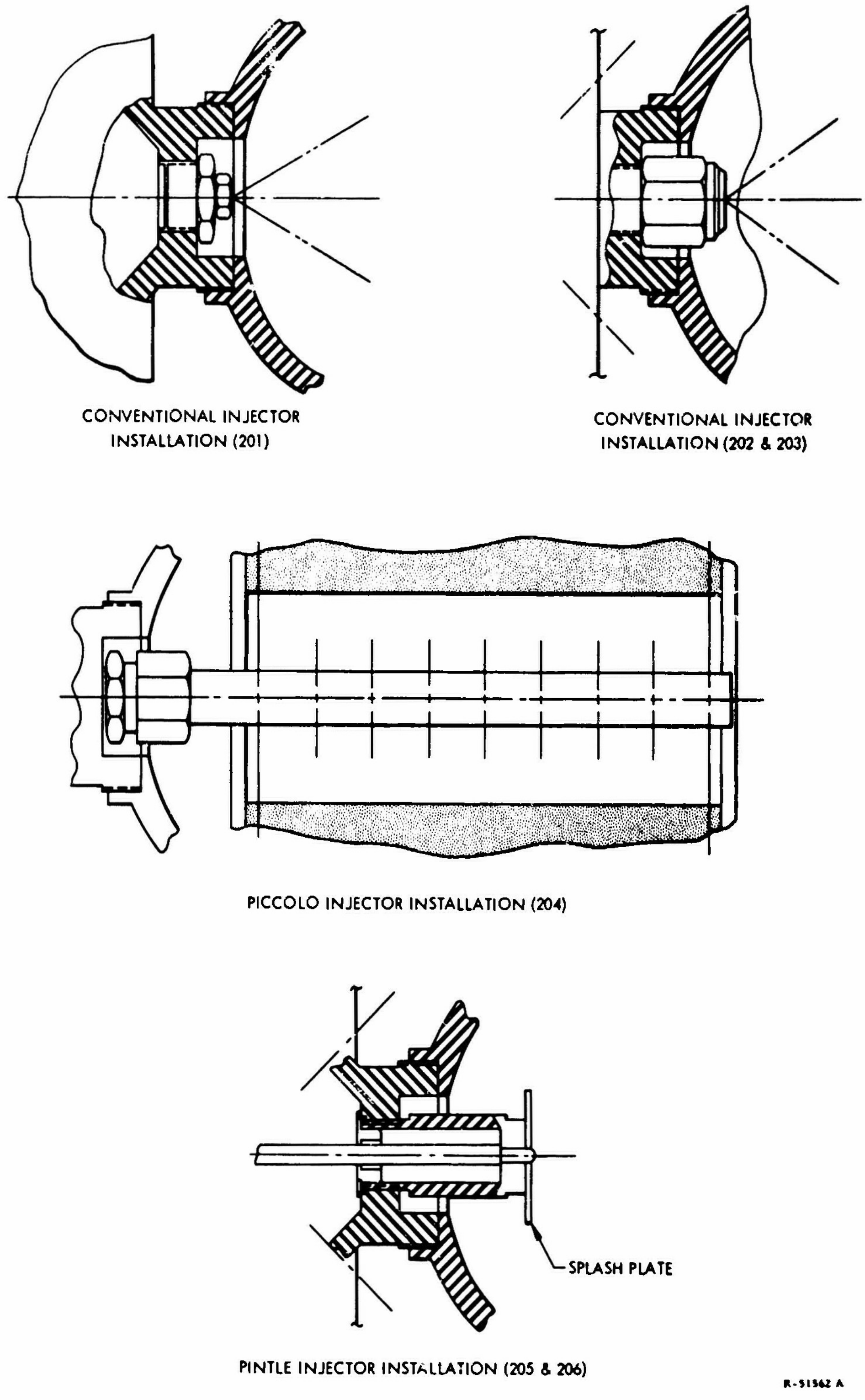


Figure 20. Basic Injector Configurations

TABLE VII

TM-1 TEST RESULTS

Test No.	Injector	Motor	Injectant	W_{inj} lb	$\dot{w}_{inj}$ lb/sec	$(P_c)_{inj}$ psia	$\dot{w}_{motor}$ lb/sec	Dt in.	A_B in.^{2}	$\dot{w}_{inj}/\dot{w}_{motor}$	W_{inj}/A_B lb/in.^{2}	Max. dp/dt psi/sec	Comments
1	201	-03	H_2O	4.73	16.9	440	2.74	1.128	141	6.17	0.0336	25,000	Terminated
2	201	-03		1.23	16.1	445	2.77	1.128	142	5.82	0.0086	18,500	Reignited - 7-1/2 sec after termination
3	201	-03		4.73	13.5	495	3.08	1.128	153	4.39	0.0309	32,000	Terminated
4	202	-03		4.73	8.95	440	2.74	1.128	141	3.26	0.0335	22,700	Terminated
5	202	-03		4.73	6.8	530	3.30	1.128	---	2.06	---	15,400	Trigger time too long-fired on blowdown
6	203	-03		4.73	14.8	492	3.06	1.128	153	4.83	---	---	Insert failure
7	202	-03		4.73	7.1	564	3.51	1.128	169	2.01	0.028	11,000	Did not terminate
8	202	-03		2.41	7.4	410	2.55	1.128	133	2.90	0.0181	14,400	Reignited - 1.4 sec after termination
9	203	-03		2.41	10.0	405	2.52	1.129	132	3.97	0.0182	25,000	Terminated
10	203	-03		2.41	6.32	440	2.74	1.128	141	2.30	0.0171	17,000	Reignited - 3 sec after termination
11	206	-03		4.48	20.8	415	2.58	1.131	134	8.06	0.0334	19,500	Terminated
12	206	-03		4.48	18.1	458	2.85	1.131	143	6.35	0.0313	17,200	Terminated
13	206	-03		1.76	24.4	515	3.20	1.131	157	7.62	0.0112	22,500	Terminated
14	204	-03		4.73	44.1	525	3.26	1.131	160	13.5	0.0296	22,500	Terminated - (See discussion)
15	206	-04		4.38	26.5	636	3.28	1.028	154	8.09	0.0284	37,500	Terminated
16	206	-04		1.17	18.8	653	3.36	1.028	158	5.60	0.0074	25,000	Reignited - 12 sec after termination
17	203	-04		4.05	16.8	651	3.36	1.03	158	5.0	0.0256	21,500	Terminated
18	203	-04		2.29	16.6	717	3.70	1.03	168	4.49	0.0136	23,600	Terminated
19	203	-04		2.14	10.0	750	3.87	1.03	174	2.58	0.0123	11,800	Reignited - 4 sec after termination
20	204	-04		2.14	18.5	735	3.78	1.028	172	4.90	0.0124	N/A	Terminated
21	204	-04		2.21	14.25	663	3.42	1.028	159	4.17	0.0139	22,500	Terminated
22	204	-04		1.25	13.2	609	3.14	1.029	148	4.20	0.0084	28,000	Terminated
23	204	-04		1.35	11.05	710	3.66	1.030	167	3.02	0.0081	---	Terminated
24	204	-04	H_2O	0.38	14.60	697	3.60	1.030	165	4.05	0.0023	28,600	Reignited

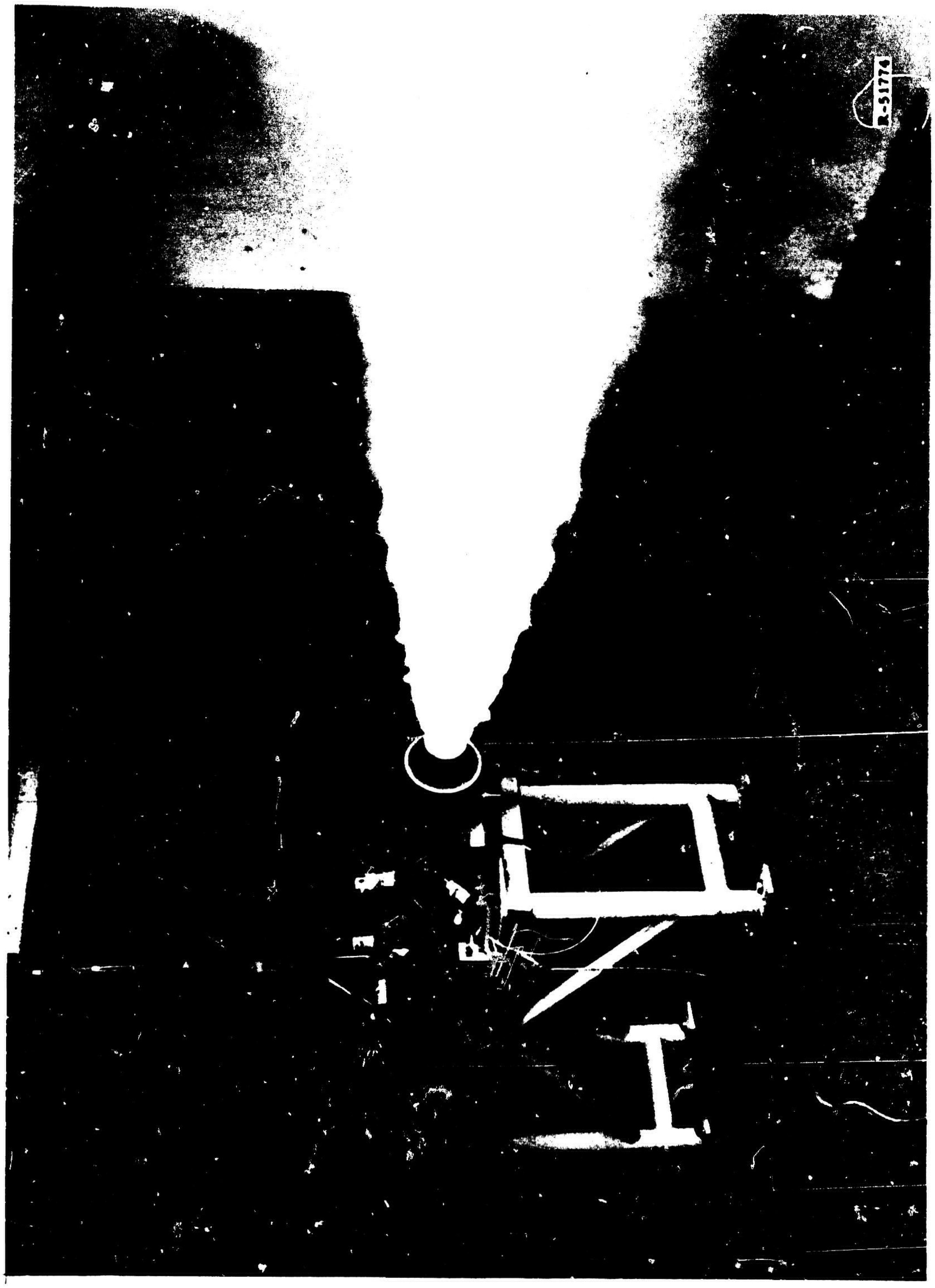
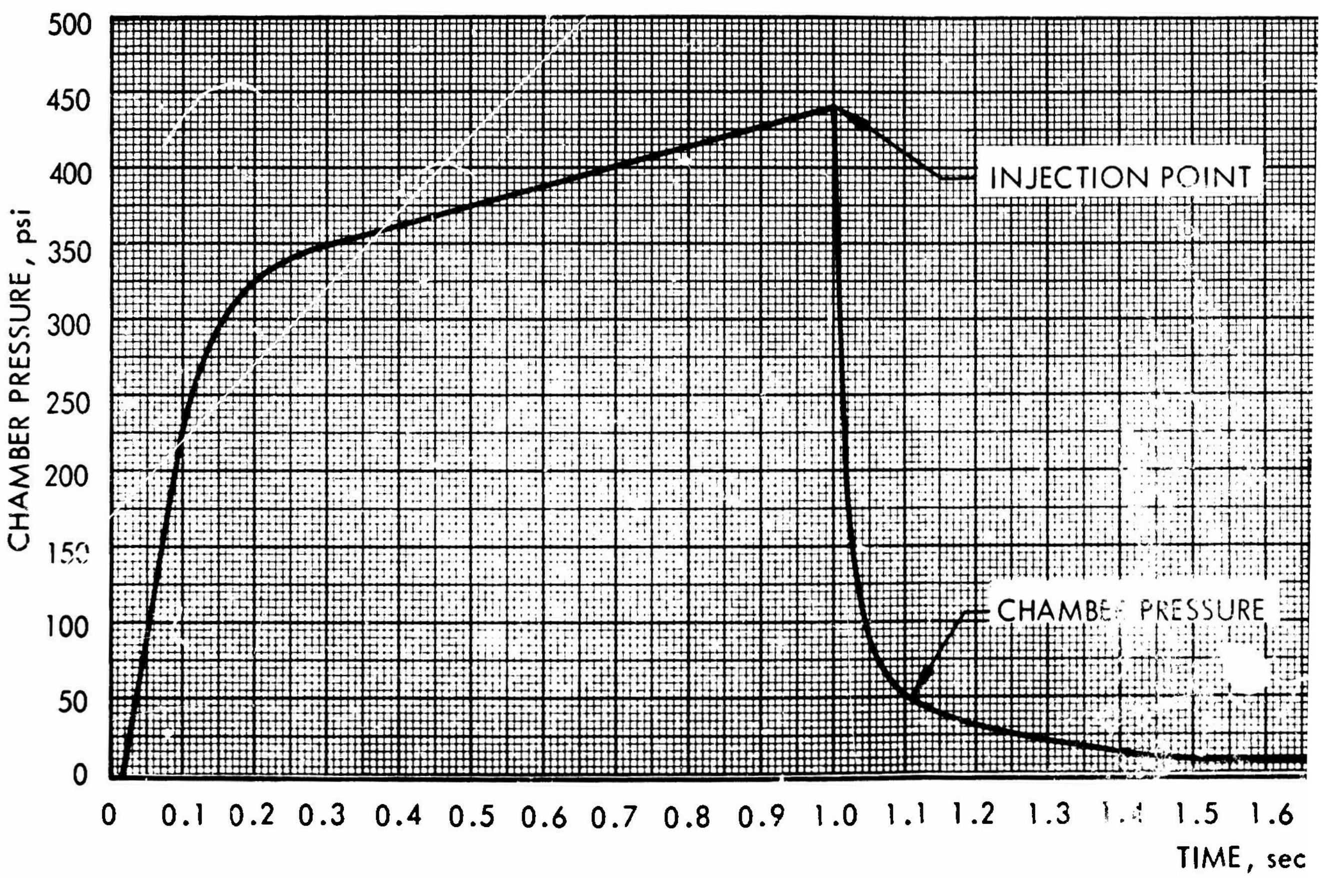


Figure 21. TM-1 Test Firing


CHAMBER PRESSURE, psi
500
450
400
350
300
250
200
100
50
0
INJECTION POINT
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.5 1.6
TIME, sec

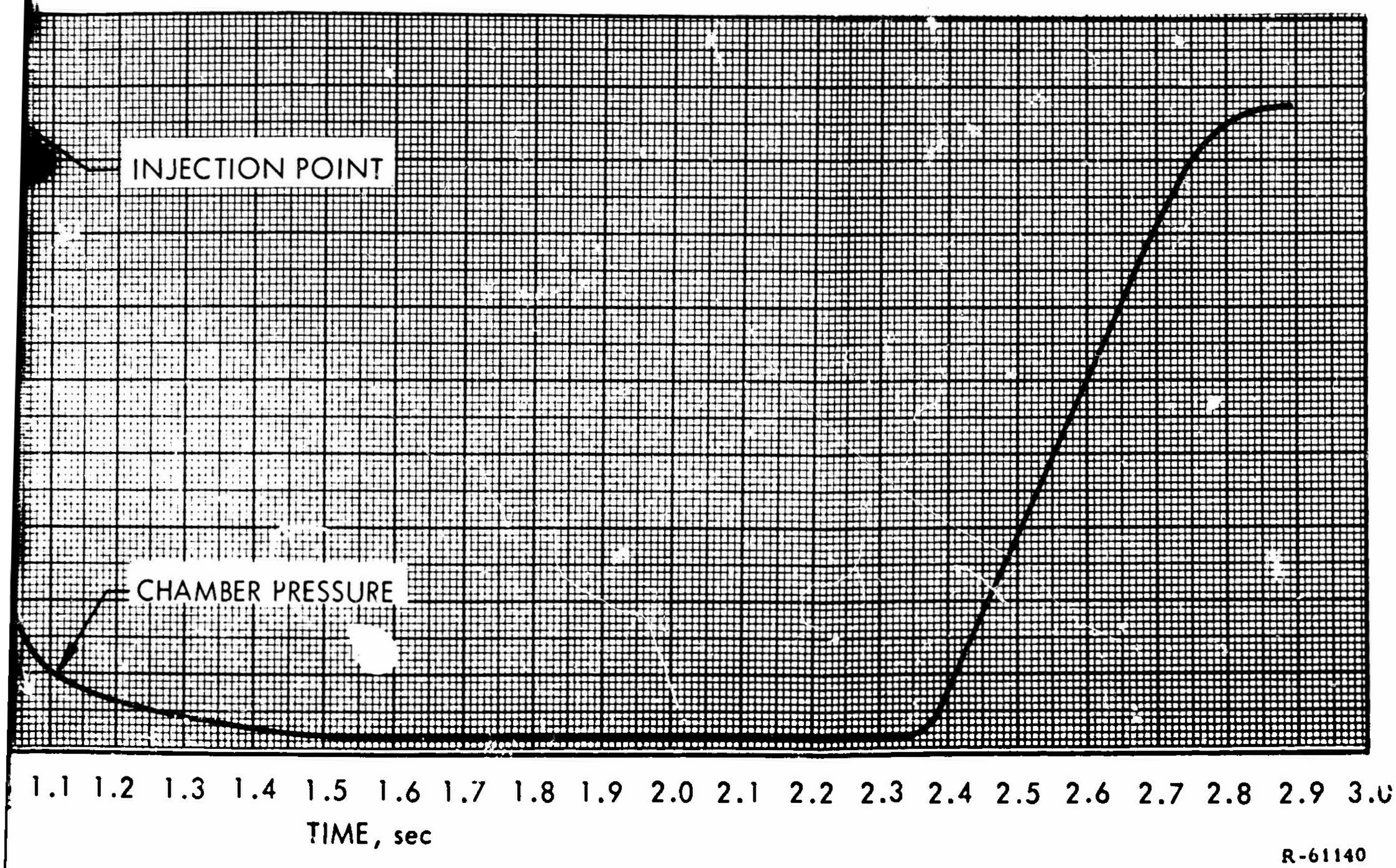


Figure 22. Chamber Pressure vs Time, Small Motor Test No. 010 (Reignition)

B

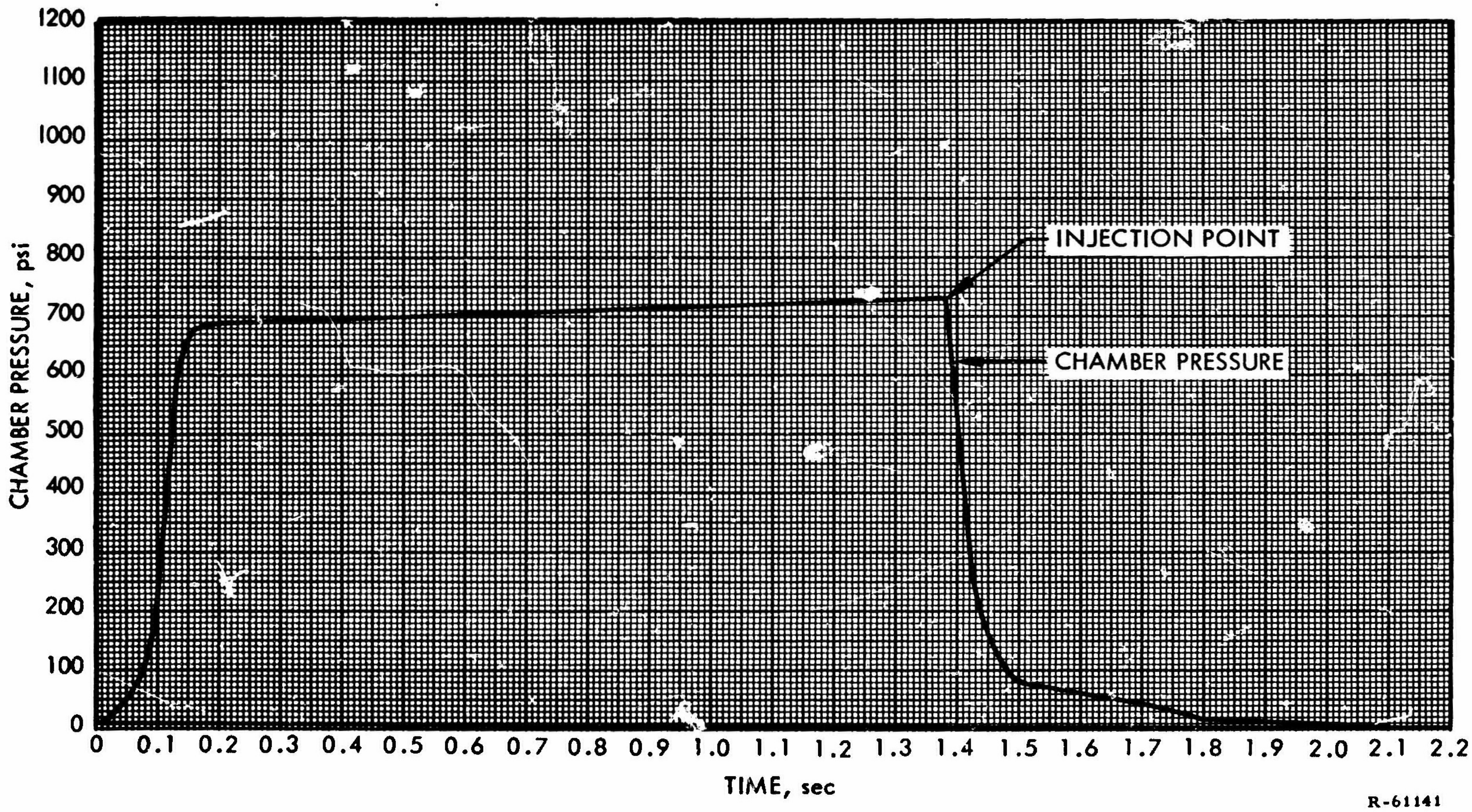


Figure 23. Chamber Pressure vs Time, Small Motor Test No. 023 (Termination)

positive seal when not actuated and therefore did not require further modification. However, difficulty was encountered with the piccolo injector (204). Initially, each of the 66 injectant holes was packed with zinc chromate putty. This allowed the piccolo injector to be filled with water without leaking. However, this method was found to be unsatisfactory when the motor was fired (test No. 14). Although combustion was extinguished, the injectant flow rate was much higher than anticipated. Visual inspection of the injector after the firing indicated that the putty sealing one of the holes had apparently been forced into the piccolo during motor chamber pressurization. The subsequent ingestion of hot gases then caused local heating which weakened the 6061 aluminum tubing in that area. Upon water pressurization this area failed, injecting most of the water at one spot on the grain. The unbalanced reaction thrust bent the tube to one side, fracturing the insulation and stripping it from the piccolo injector. Figure 24 shows the injector after the firing.

Subsequent firings of this injector utilized small aluminum disks which were bonded over each hole and acted as burst diaphragms. Figure 25 shows prefire and postfire views of the injector. Figure 26 shows a 204 injector after test No. 24, during which the motor reignited.

Test No. 6 was the first firing with the 203 injector. This injector incorporated a stamped-metal swirl plate held in place with a snap ring. Upon motor pressurization, the air bubble (ullage) in the injectant chamber collapsed. The resulting reverse wash of water through the swirl plate lifted the snap ring from its seat and ejected the swirl plate back into the injectant cylinder. (After the firing, both these parts were found in the bottom of the injectant cylinder.) The loss of the swirl plate caused the water to be injected in a solid axial stream rather than in a cone during the firing. A rise in chamber pressure of approximately 15% was noted during the period of fluid injection and resulted from throat blockage by the solid water stream.

Data for test No. 4 are incomplete because of an inadvertent delay in triggering of the injection system, which resulted in injection initiation after web burnout. As experience was gained from testing of the different configurations, it was possible to set the time of injection within ±0.3 sec, and no other malfunctions of this type occurred.

3.1.2.4 Test Results

Each candidate injector was capable of extinguishing combustion in a solid propellant motor for a characteristic set of injectant flow parameters. Three of the injectors (the 203, 204, and 206) demonstrated the capability of extinguishment of a burning radial slot similar in configuration to the slot found between the segments and closures of the Titan III-C SRM configuration.

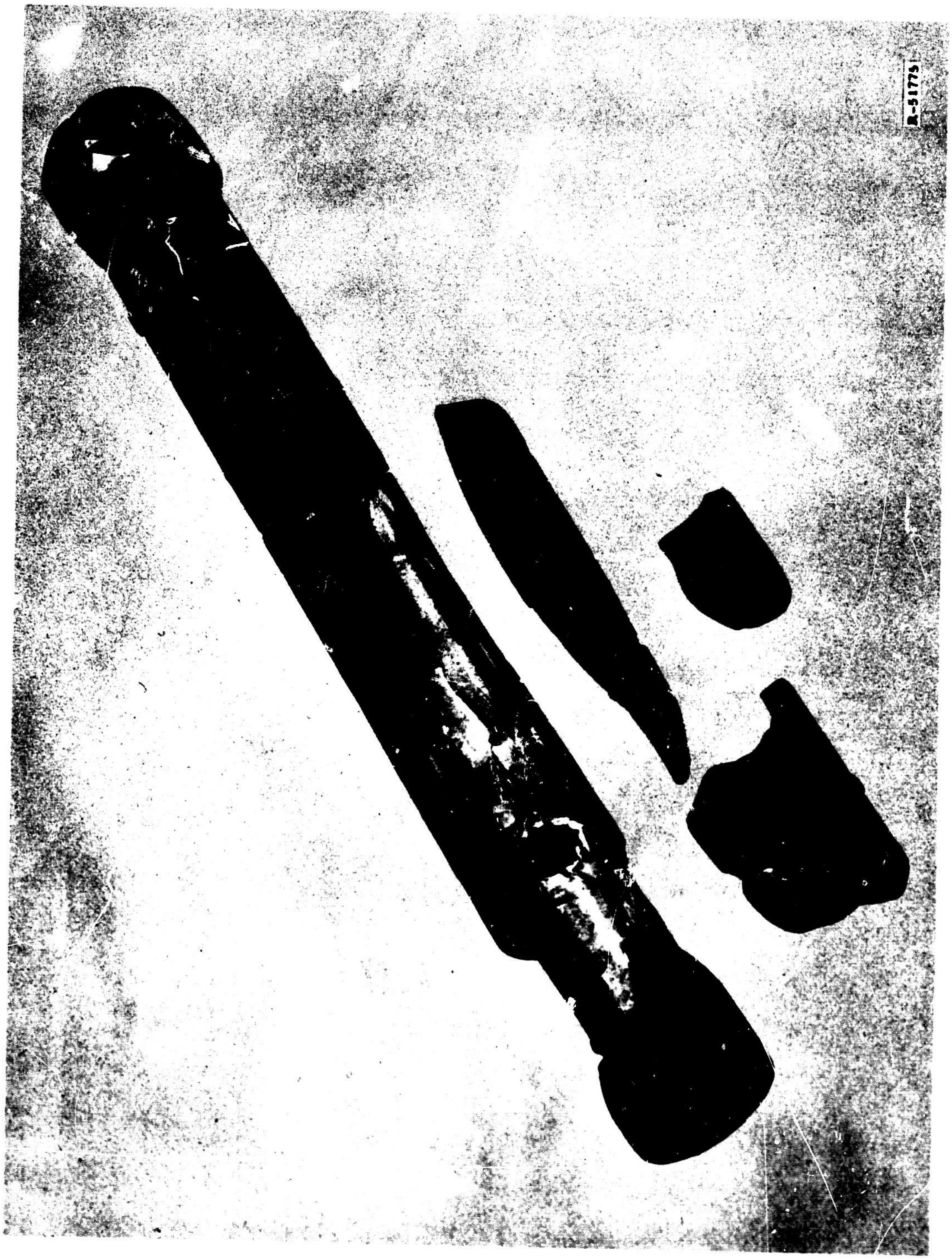


Figure 24. View of 204 Injector After First Firing

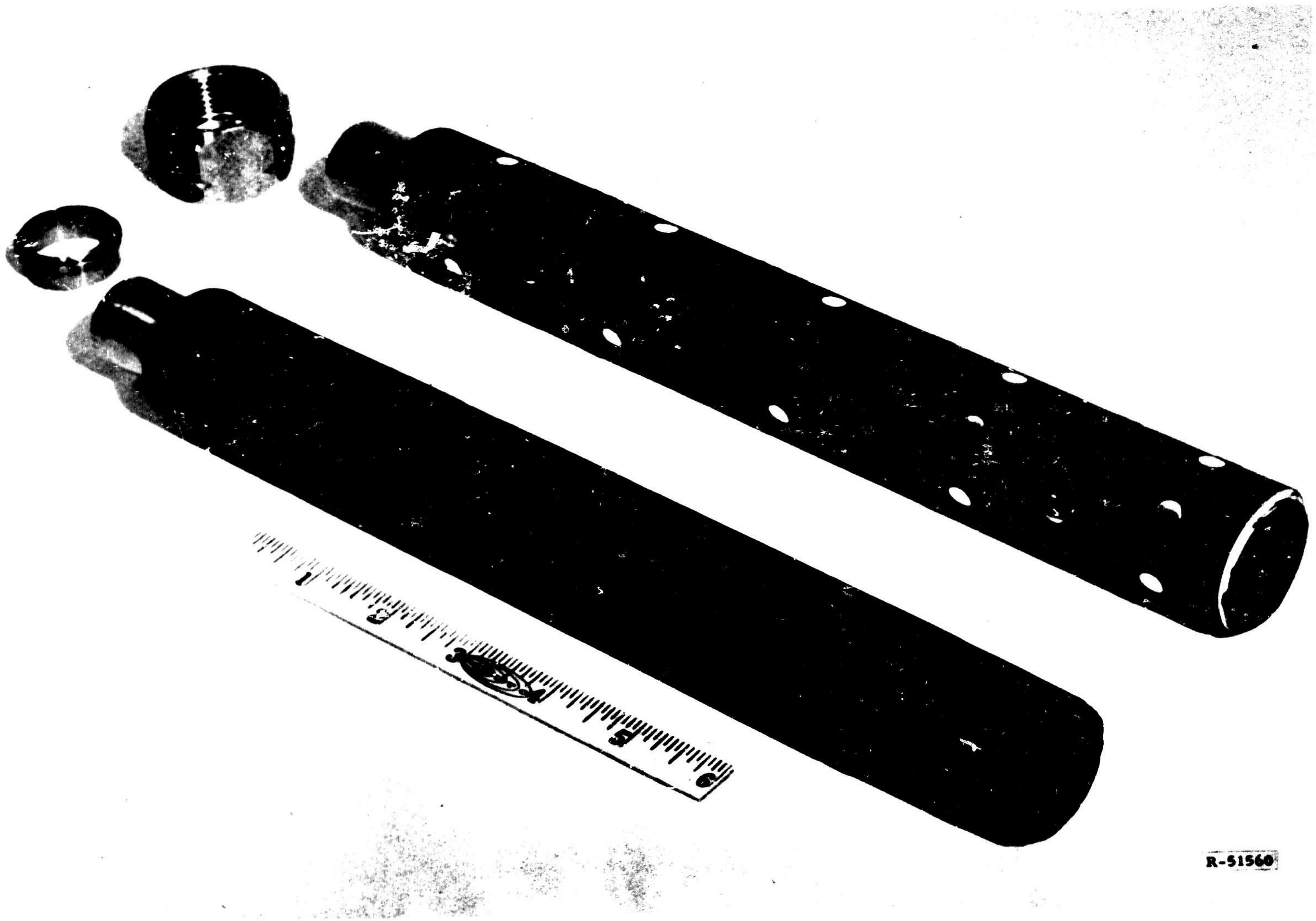


Figure 25. Prefire and Postfire Views of Piccolo Injector

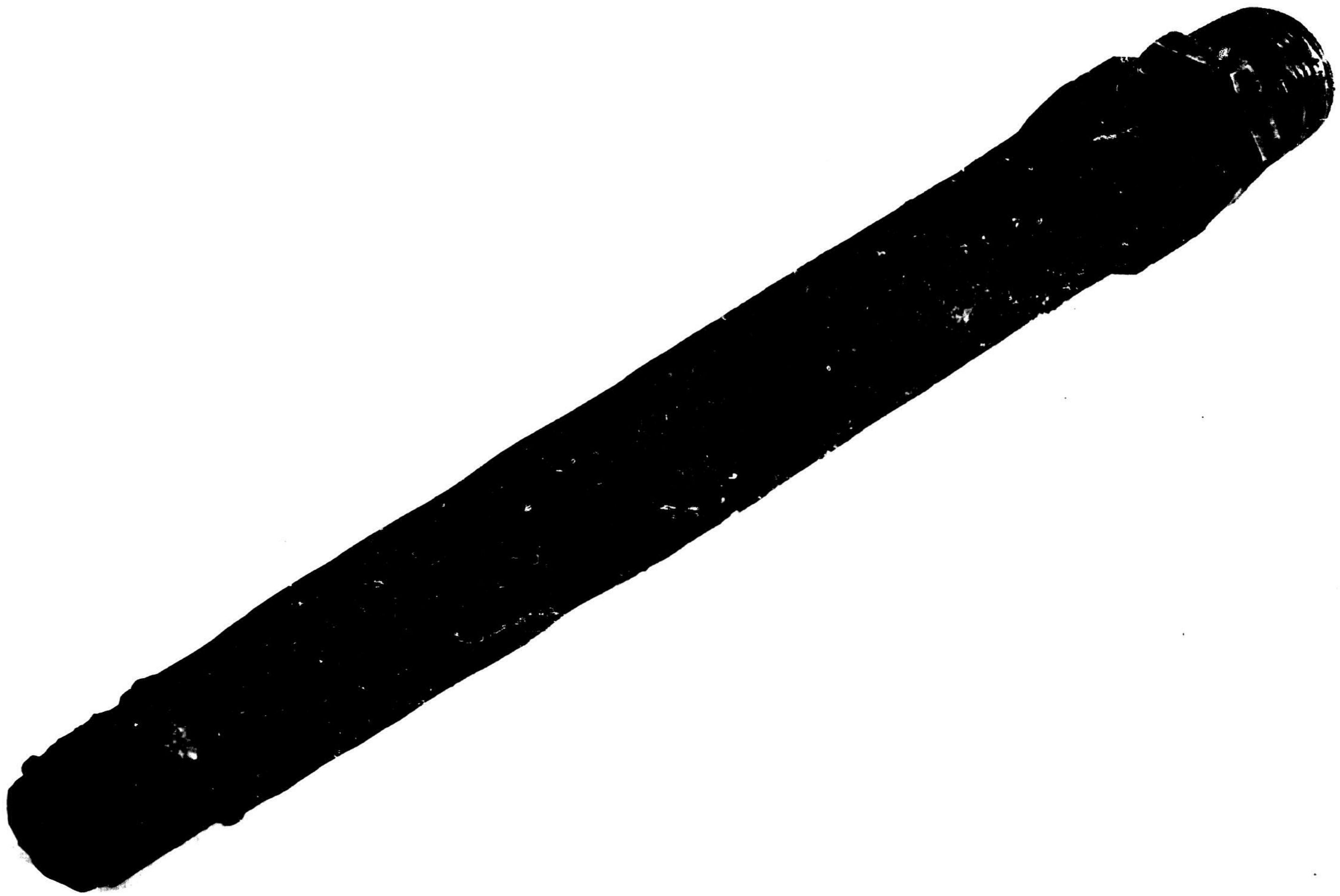


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Figure 26. View of Piccolo Injector After Motor Failed to Terminate

The injectant requirements, charge weight, and flow rate necessary for complete extinguishment were similar for the head-end (pintle and commercial spray nozzle) injector designs. The piccolo injector, however, exhibited considerably lower requirements, indicating more efficient use of the injectant. The reasons for this increased effectiveness will be discussed in detail in section 3.13.

Extinguishment of the solid propellant grain by water impingement has no apparent effect on the surface composition. In test No. 5, a previously fired and extinguished grain was reused, and both ignition and steady-state burning were as expected.

In subsequent tests, grains were reused whenever possible without experiencing any problems. Figure 27 shows a typical grain, -03 configuration, after one extinguishment.

3.1.3 Analysis of Small Motor Test Results

Evaluation of the small motor test results indicated that a critical injection rate and injectant quantity existed for a given motor test condition. On this basis, it was found that two parameters could be used to define the critical injection mode for varying motor test conditions, i.e., chamber pressure and propellant mass flow as defined by nozzle size and grain configuration. These parameters are the ratio of average injectant mass flow rate to motor propellant mass flow rate ($\dot{w}_{inj}/\dot{w}_{motor}$) at the initiation of termination and the total injected mass to propellant burning surface area (W_{inj}/A_B) at injection. These parameters indicated an inverse relation in defining the critical mode of extinguishment. An increase in the mass flow ratio resulted in a decrease in the value of the mass area ratio (W_{inj}/A_B) required for complete extinguishment.

Correlation of all small motor test data by critical injection parameters is presented in figures 28, 29, and 30. The areas of incomplete and complete extinguishment are divided by the critical injectant parameter line. The limits within which the critical injection parameter remains valid have not been clearly defined. However, it is apparent that there is a lower limit on the rate of injection, below which no quantity of injectant will extinguish the motor. It is postulated that at some lower limit the injectant does not form a complete film over the entire propellant surface. Either the water is evaporated at such a rate that liquid does not reach all parts of the burning surface, or the mechanical efficiency of the injector falls to a point that allows areas of the burning surface to remain dry. From an engineering standpoint, the high limit on the curve is of more interest because the area of minimum injection quantity lies in this region. The minimum injectant quantity is limited by the fact that injectant must

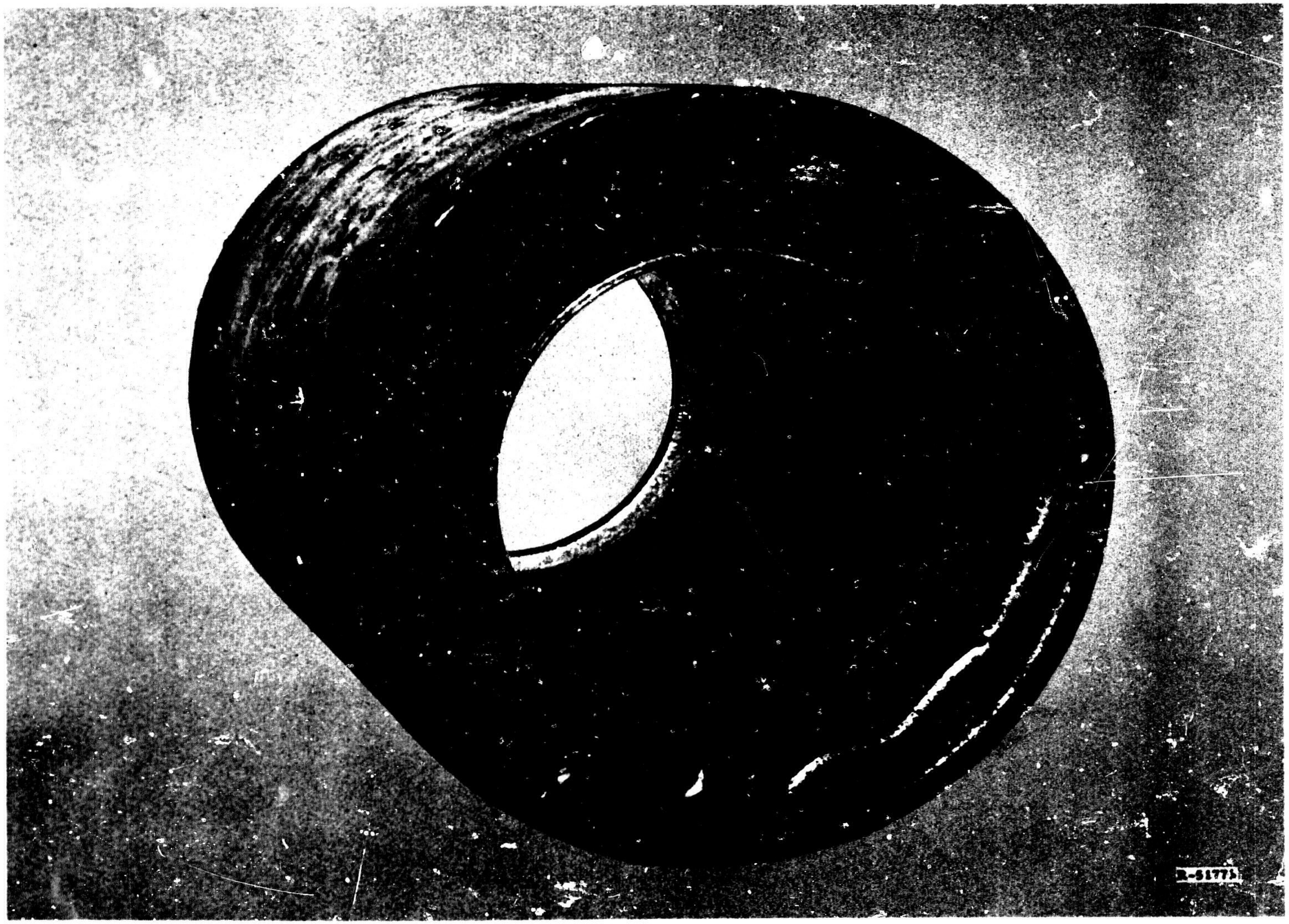


Figure 27. Propellant Charge After One Extinguishment

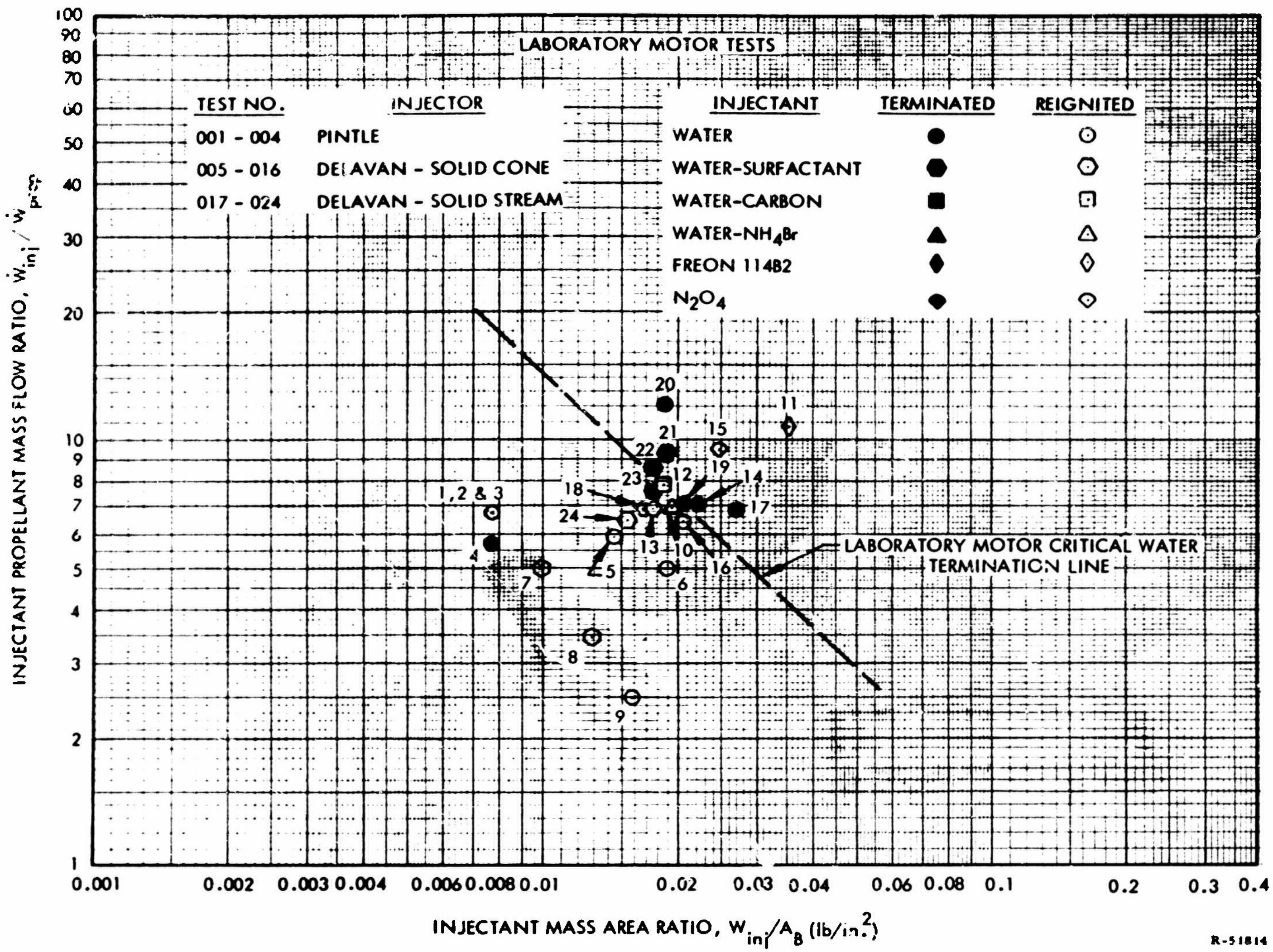


Figure 28. Extinguishment Pa, ameters, Laboratory Motor Tests

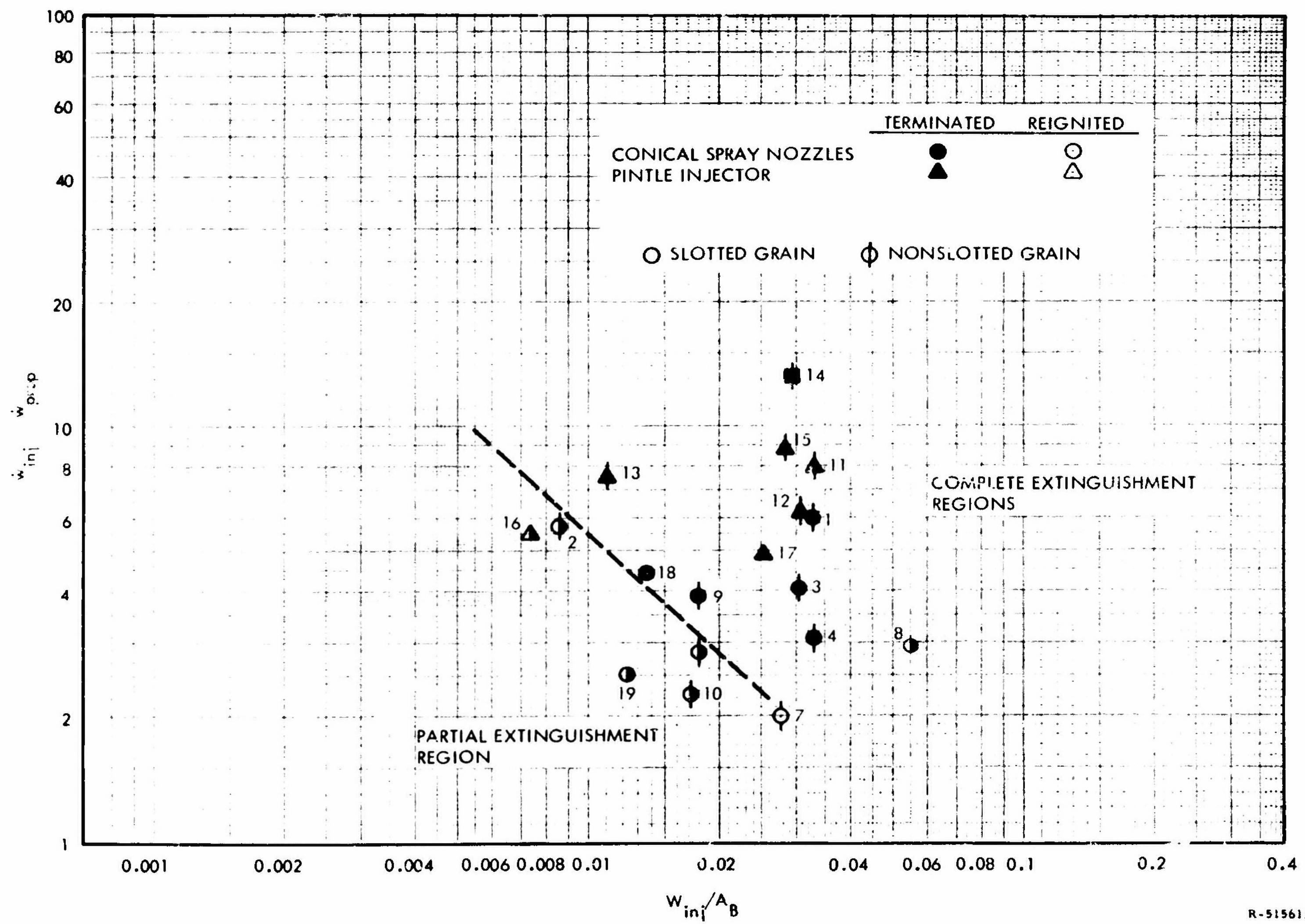


Figure 29. Extinguishment Parameters for Head-End Injectors, TM-1 Test Motors

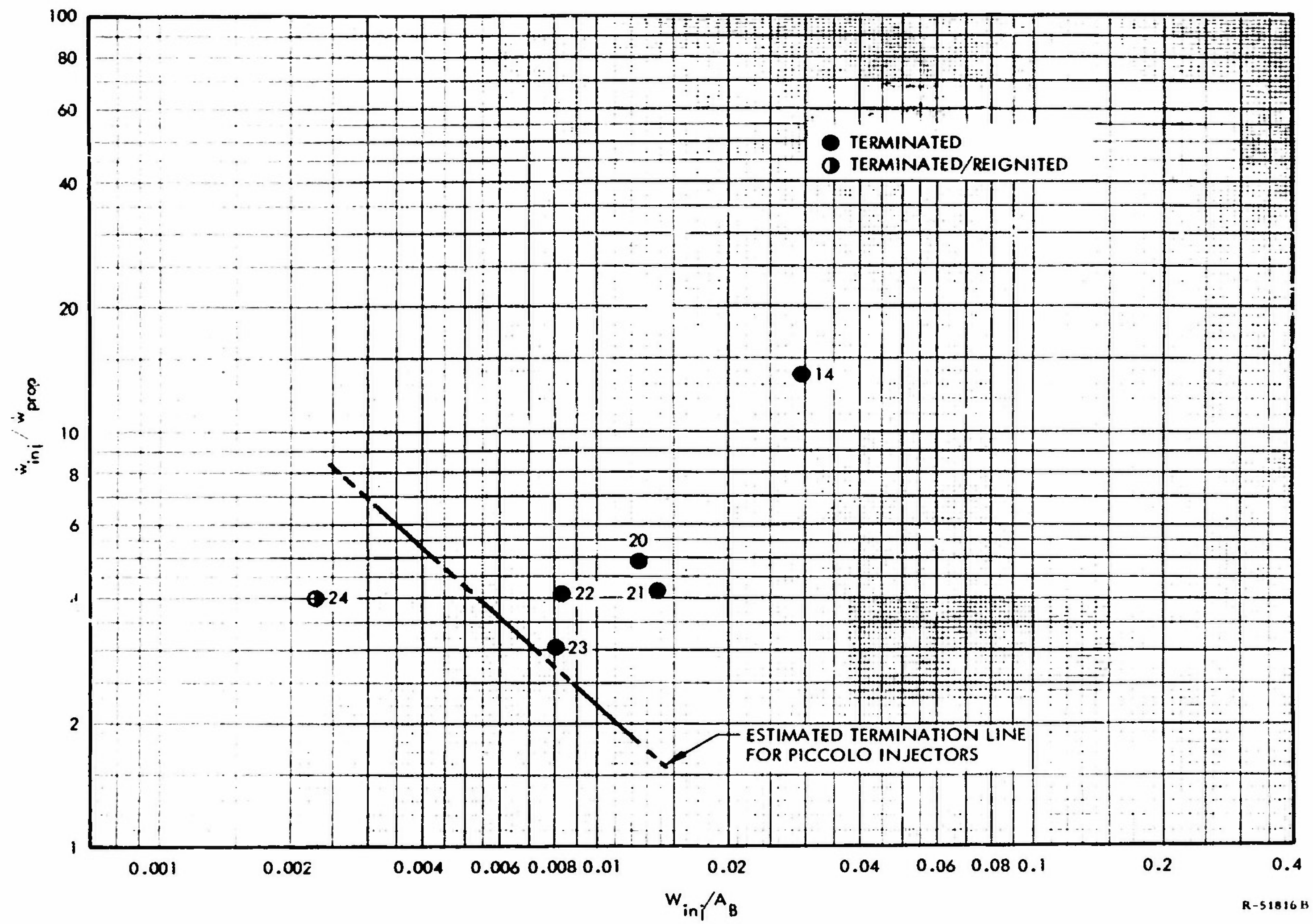


Figure 30. Extinguishment Parameters for Piccolo Injectors, TM-1 Test Motor

cover the entire propellant surface for an interval of time sufficient to cool the surface below the ignition temperature. Undoubtedly, there is a minimum injectant quantity required to remove sufficient heat from the burning surface to cool it below the combustion temperature. However, this quantity is probably small in comparison with the losses to the hot gases and the losses resulting from the inefficiencies of injector coverage. At present, there are insufficient empirical data to define the upper and lower portions of the curve.

A significant difference was noted between the injectant requirements of the laboratory motor and the TM-1 motor (see figures 28 and 29). Because the critical parameter curves are not size dependent, one curve should apply to all solid propellant motors. Analysis of the data, however, shows that significantly more injectant is required to extinguish the laboratory motor than the TM-1 motor.

Although the cause for the increase has not been empirically determined, it is probably the result of the differences in motor grain geometry and injector efficiency with possible secondary effects resulting from the fact that in the laboratory motor, the ratio of free volume to propellant surface area is much greater than normally found in a solid propellant motor.

It can be postulated that the head-end injection in the TM-1 motor tests more effectively utilizes the water by providing a longer dwell time at the propellant surface because of the higher longitudinal velocity component of the injectant. Scaling effects of the injector nozzle size were also suspect because the high pressure drops used with the laboratory injector nozzle result in a small fluid droplet size. Although high droplets velocities may be achieved, the momentum of the small individual droplets is low, and the percentage of droplets reaching the propellant surface is diminished by drag forces and fluid vaporization.

The data obtained from the TM-1 tests with the piccolo injector did not correlate with the line obtained from the test results for the head-end injectors. The piccolo was found to be significantly more effective in dispersing the injectant than the head-end injectors. The data obtained from tests using the piccolo injector were not sufficient to accurately establish a critical parameter line. However, if it is assumed that a similar type of line (-1 slope) is applicable, the extinguishment line for piccolo injectors lies in the region shown on figure 30.

The complete reason for the apparent effectiveness of the piccolo injector is not known; however, part of the advantage may be attributed t the manner in which the injectant charge weight was recorded. Only water

displaced by the piston was considered in the data reduction calculations; the water remaining in the injector after the injection phase was not considered for the head-end injector. This quantity of water is small compared to the quantity injected and may be disregarded. With the piccolo injector, however, this quantity is quite large, and it is reasonable to assume that the water drains out of the injector and provides some extinguishing effect. This may make a significant contribution to the extinguishment.

Because the increased effectiveness of the piccolo injector could not be completely attributed to this unaccounted for water, the efficiency was then considered in terms of the combustion termination mechanism. The piccolo injector is designed to provide a solid stream that impinges directly on the burning surface, while the head-end injector normally provides a coarse spray that contacts the burning surface. The head-end injector is apparently not as efficient as the piccolo injector in forming a continuous film; thus, it is not as efficient in transferring heat from the surface. In addition, the geometric effects are such that direct impingement results in a longer stay time on the surface, increasing the utilization of the injectant. With the piccolo injector, the injectant is much less likely to lose heat to the chamber gases because of the shorter distances traveled and the fact that the fluid is injected in a solid stream rather than in a spray. These factors, individually or in combination, may explain the increased effectiveness of the piccolo injector.

3.2 SUBSCALE MOTOR TESTS

A total of eight subscale motor tests was conducted for the purpose of evaluating the pintle injector and to establish flow rates and injectant quantities (critical design parameters) required for termination of TM-3A sized motors.

3.2.1 Test Hardware Description

All subscale tests were conducted in a standard UTC test motor designated as a TM-3. This motor is a heavy-duty test motor designed specifically for development testing at UTC. Figure 31 shows a typical cross section of the TM-3A motor and typical performance data for motors of one and two segments. All components of the motor are designed for maximum versatility, high structural safety margins, and ease of refurbishment. The philosophy of simple designs with high safety margins was applied to all components designed specifically for this test series.

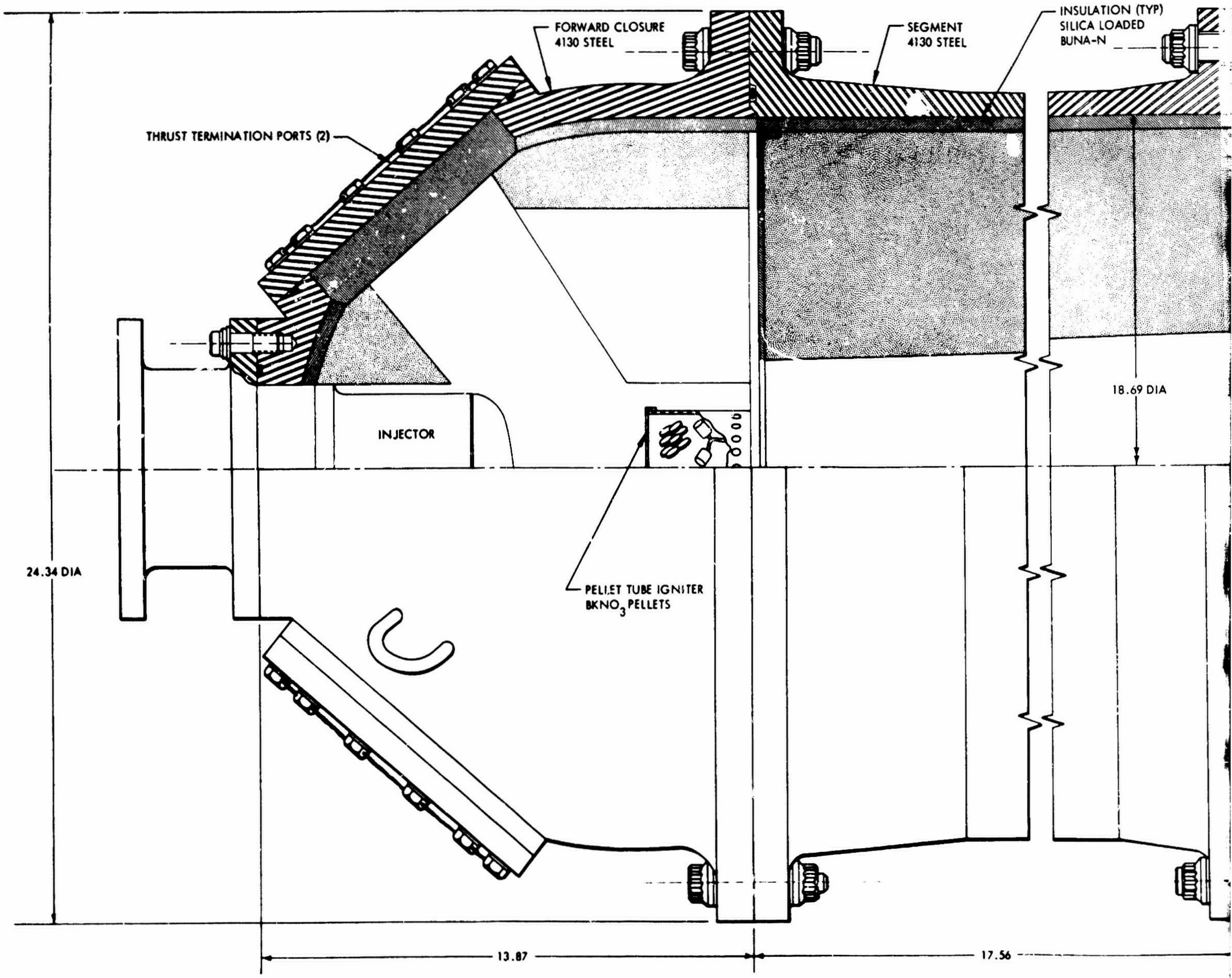
A variety of segment and closure grain designs are available which may be combined to provide many different motor configurations. The motors used on these tests utilized segments and closures which were designed to provide grain configurations similar to those found in large solid propellant motors such as the Titan III-C SRMs. The internal grain configuration varied over the test series, but basically consisted of star-port grain in the forward closure (Titan III-C subscale), either cylindrical or tapered-port segment grains, and a cylindrical-port grain in the aft closure.

The UTP-3001 propellant was used in all motor components. This is the same propellant used in the laboratory and small motor tests.

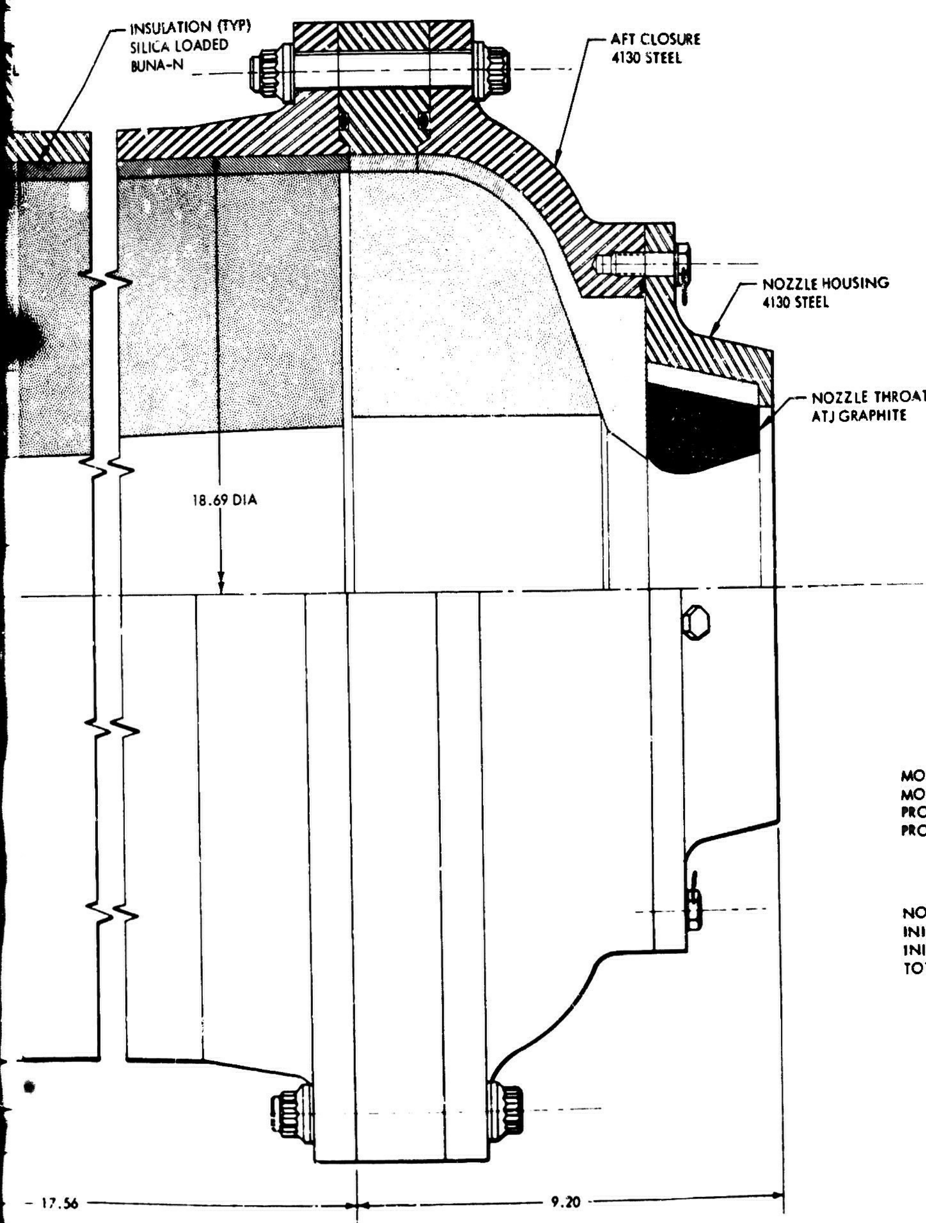
Because the injector utilized the motor igniter port, a pellet tube igniter was used to ignite the TM-3A motors. The igniter consists of a perforated paper tube filled with $BKNO_3$ pellets and initiated by the U.S. Flare* 207A squib. The igniter was located in the segment port and held in place with styrofoam supports.

The pintle-type injector developed in the small motor testing phase was selected for the TM-3A firings. Selection of an injector system was based on several considerations. On the basis of the TM-1 test results, the piccolo injector would be the obvious choice; however, it was the opinion of UTC that an injector of this type (requiring a rigid member suspended

* U. S. Flare Corp., Saugus, California



FORWARD CLOSURE
4130 STEEL
SEGMENT
4130 STEEL
INSULATION (TYP)
SILICA LOADED
BUNA-N
THRUST TERMINATION PORTS (2)
INJECTOR
18.69 DIA
24.34 DIA
PELLET TUBE IGNITER
$BKNO_3$ PELLETS
13.87
17.56



TYPICAL PERFORMANCE DATA

	1 - SEGMENT	2 - SEGMENT
MOTOR LENGTH (in.)	44.51	62.07
MOTOR DIAMETER (in.)	24.34	24.34
PROPELLANT WEIGHT (lb)	400	640
PROPELLANT CHARGE CONFIGURATION		
FORWARD CLOSURE	INTERNAL BURNING 8 POINT STAR	
SEGMENT	INTERNAL BURNING TAPERED TUBE	
AFT CLOSURE	INTERNAL BURNING TUBE	
NOZZLE THROAT DIAMETER (in.)	3.39	3.84
INITIAL PROPELLANT SURFACE AREA (in.^{2})	1,900	2,450
INITIAL MASS FLOW RATE (lb/sec)	45.4	58.6
TOTAL IMPULSE (lb-sec)	94,400	150,000

R-61162

Figure 31. Typical TM-3A Test Motor

B

from the forward closure) would compromise motor design and present so many structural and thermodynamic problems that it would never find application in an operational system. Several ideas for collapsible or nonrigid piccolos were also investigated. Although these schemes solved the structural problems of a rigid member, they presented deployment problems which made their success as a system doubtful. Thus, the choice was limited to the several head-end injectors tested in the TM-1 firings; the pintle injector was ultimately selected. This injector was selected over the other head-end systems on the basis of its improved water distribution over the propellant located in the forward closure of the motor. Because more than 50% of the motor surface area is in the forward closure of the one-segment configuration, proper coverage of this area was considered essential.

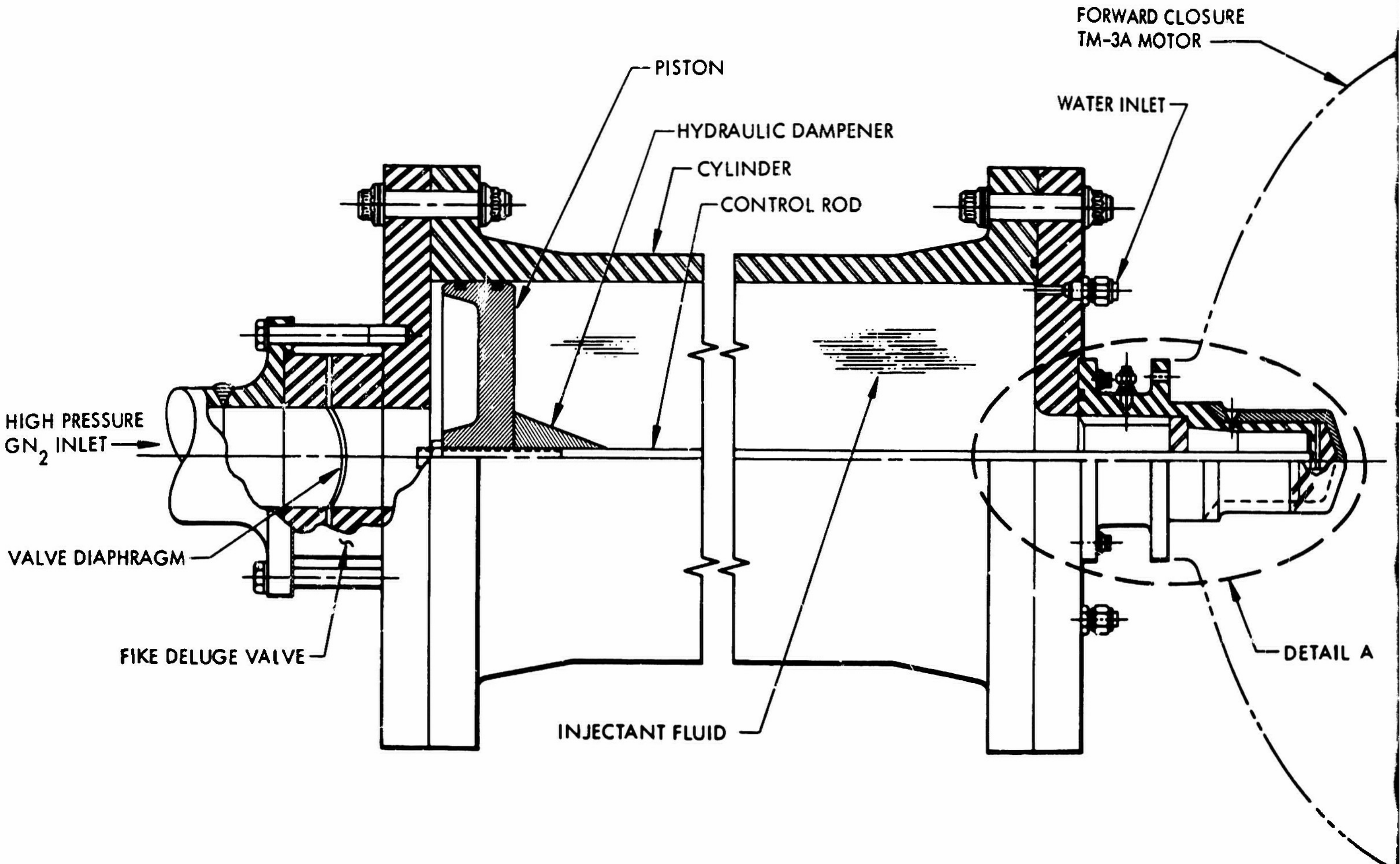
The final injector design, shown in figure 32, was essentially a scaleup of the TM-1 injector incorporating a cylinder and GN_2-driven piston to inject the water into the motor. As in the TM-1 system, the water flow rate was controlled by varying the driving pressure on the piston, and the quantity of water injected was controlled by varying the cylinder volume ahead of the piston.

The injector incorporated a movable pintle and was designed to provide a progressive flow pattern starting in the forward closure and sweeping down the port to the aft closure. The injector nozzle, swirl plate, and pintle are shown in figure 33.

Examination of the propellant charge configuration revealed two potentially difficult areas to extinguish: (1) The forward closure (in addition to the large surface area in the forward closure which requires a large quantity of injectant, the forward portion of the star points are behind the injector face and are shadowed from direct impingement) and (2) the slots existing between the propellant charges of individual segments or closures. The forward face of each slot is completely shadowed by direct injectant impingement and will require the water to be deflected into the slot.

To improve the probability of extinguishment of the star points directly adjacent to the injector housing, a circle of injector nozzles was located around the housing and directed to impinge on the star points.

To improve the flow of injectant into the downstream slots, the injector incorporated a swirl plate near the injector exit plane. This swirl plate acted as the injector orifice and served to induce a radial velocity component to the injectant. With this radial velocity, the water would tend to move down the port in a circular motion and upon reaching a slot would be accelerated into the slot.


FORWARD CLOSURE
TM-3A MOTOR
PISTON
HYDRAULIC DAMPENER
CYLINDER
CONTROL ROD
WATER INLET
HIGH PRESSURE
GN2 INLET
VALVE DIAPHRAGM
FIKE DELUGE VALVE
DETAIL A
INJECTANT FLUID

A

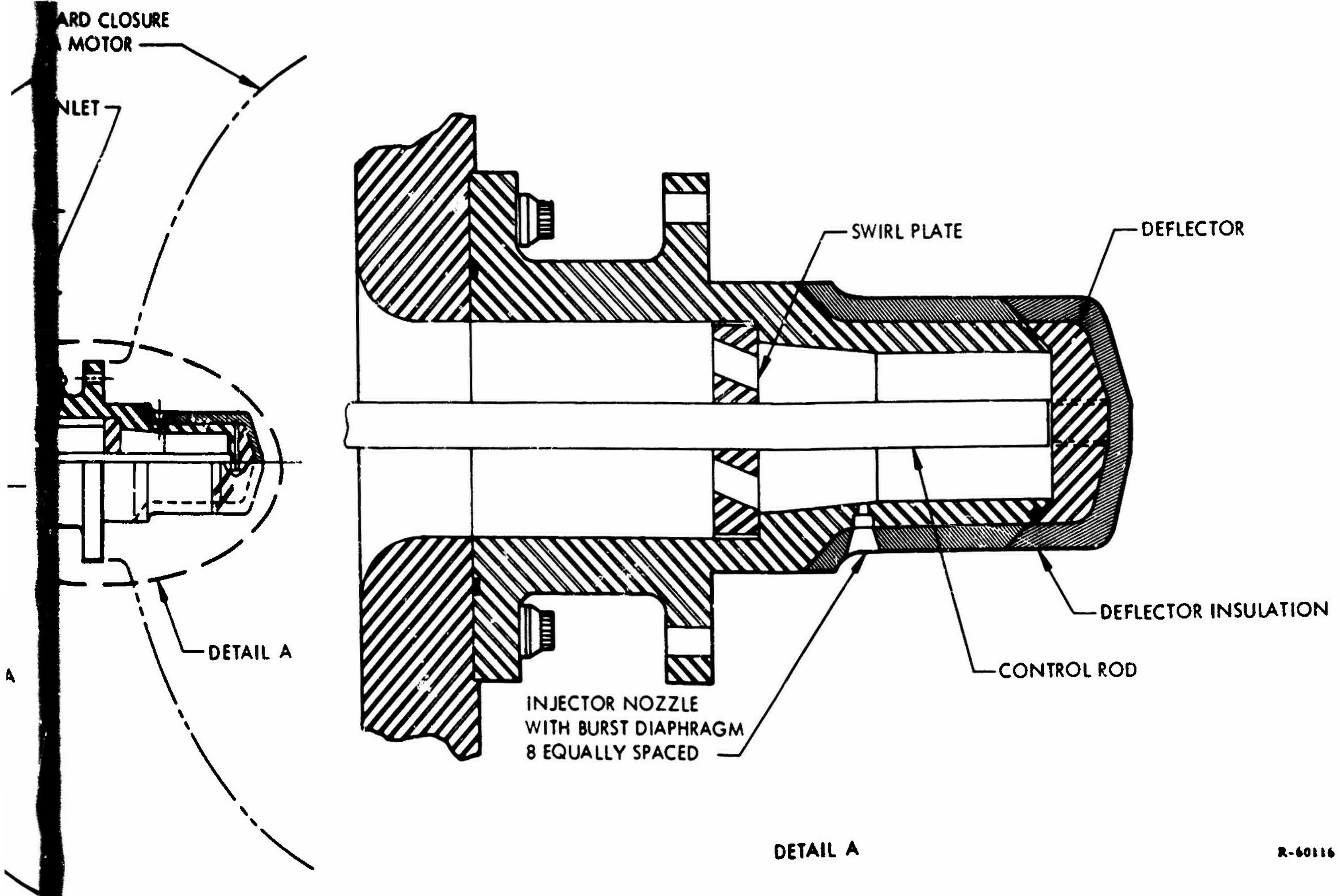


Figure 32. Injection System, TM-3A Motor Tests

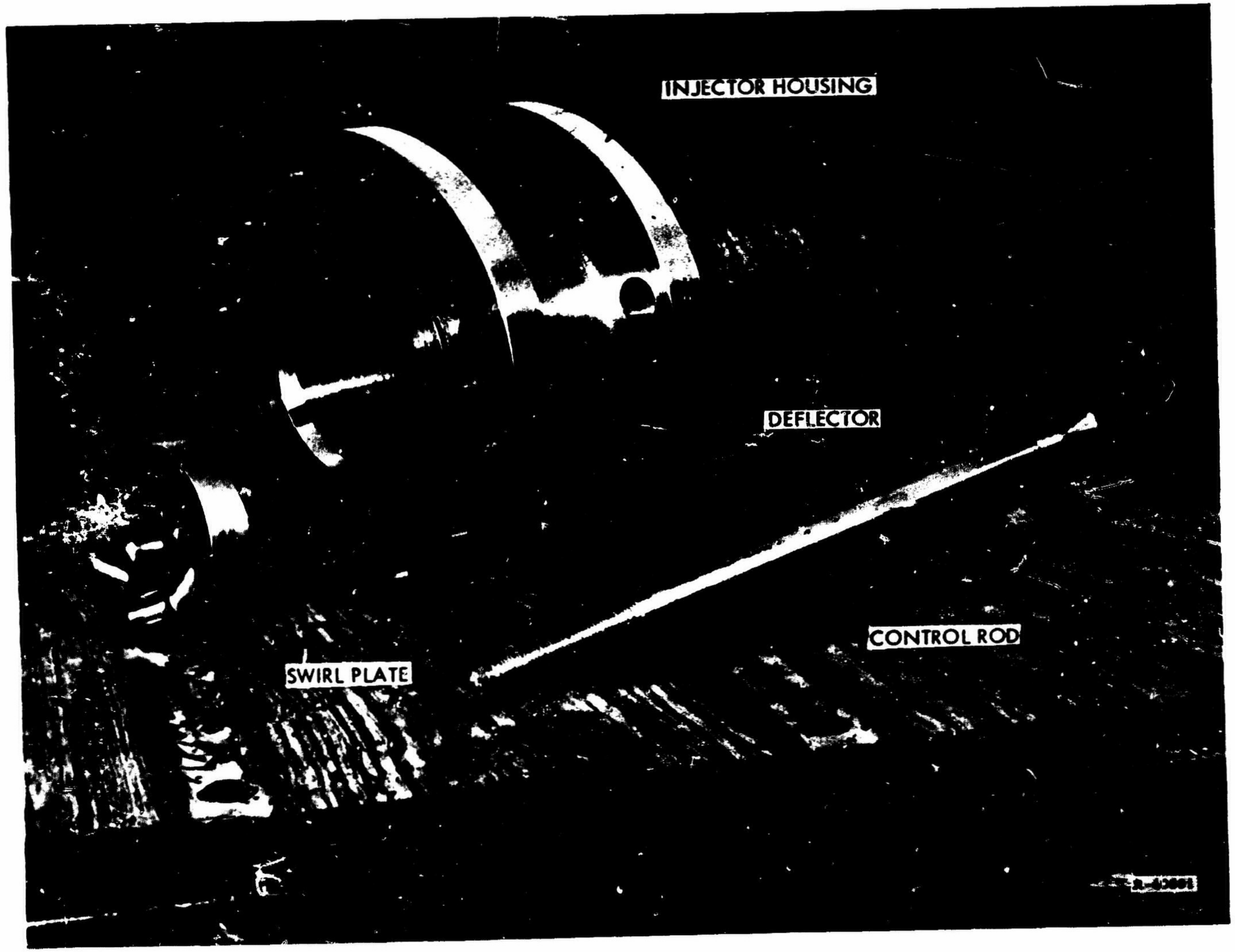


Figure 33. TM-3A Injector Showing Pintle and Swirl Plate

A control rod was used to mechanically link the piston to the deflector. Changes to the length of the control rod varied the volume ahead of the piston and thereby provided a means of varying the injectant charge weight. By using a rigid connection between piston and the deflector, the injector sweep rate and spray density was controlled for any flow rate.

A hydraulic dampener was located on the piston face to absorb the inertial energy gathered by the piston during the piston stroke. The dampener utilized a cone which was mounted over the control rod and attached to the piston face. This cone served to close the annular opening between the control rod and the injector barrel, thereby trapping a portion of the injectant ahead of the piston.

Actuation of the injector was accomplished with a FIKE* explosively actuated deluge valve located in the primary GN_2 line. This valve utilizes a steel diaphragm which may be explosively ruptured on command.

All components of the injector were fabricated of heat treated and tempered 4130 steel. This provided the injector with adequate strength to withstand injection pressures as high as 3, 100 psi.

The injection system consisted only of the injector, the explosively actuated valve, a GN_2 supply tank, and associated plumbing. The injection system is shown in figure 34, and a plumbing schematic is shown in figure 35.

The operating sequence of the injection system is as follows: The injector is prepared for testing by adjusting the control rod to the proper length and then charging the volume ahead of the piston with water. The primary facility valves, bypass valves, and vent valves are closed and the GN_2 supply tank is pressurized. The actuator valve is then armed, and the test bay is cleared of personnel. (The remaining operations are remotely controlled from the blockhouse.)

The bypass valve is then opened to equalize the pressure ahead of the actuator valve. (The pressure surge which would result from opening the facility valve without pressure equalization would very likely damage the actuator valve.)

The facility valve is then opened, and the test countdown is started. Opening of the actuator valve is controlled by a counter which initiates the test motor and then at a predetermined time lapse, sends an electrical impulse to the detonator in the actuator valve which in turn detonates the explosive charge, rupturing the steel diaphragm.

* FIKE Metal Products, Blue Spring, Missouri.

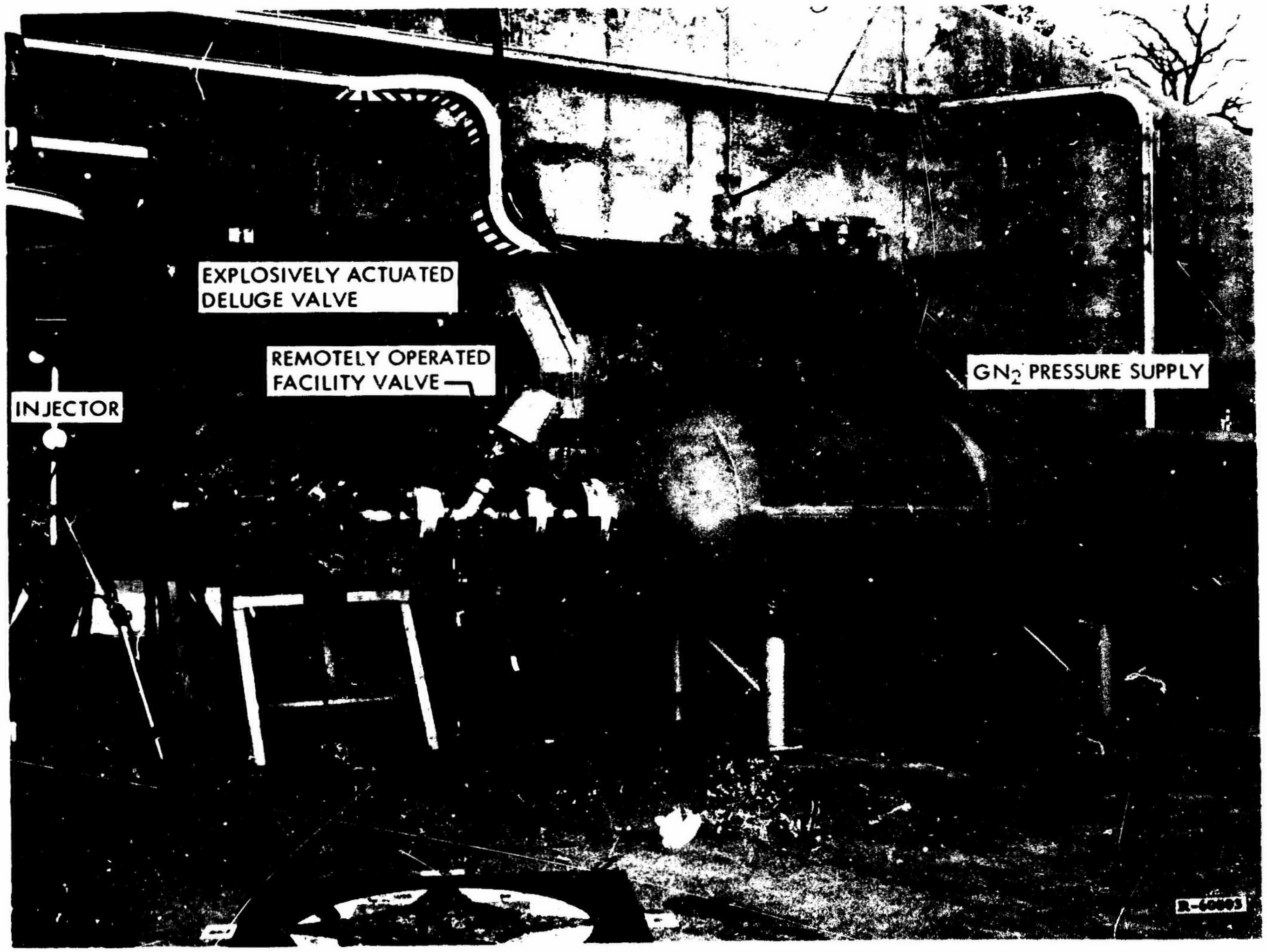


Figure 34. Injection System TM-3A Motor Tests Showing the GN_2 Tank

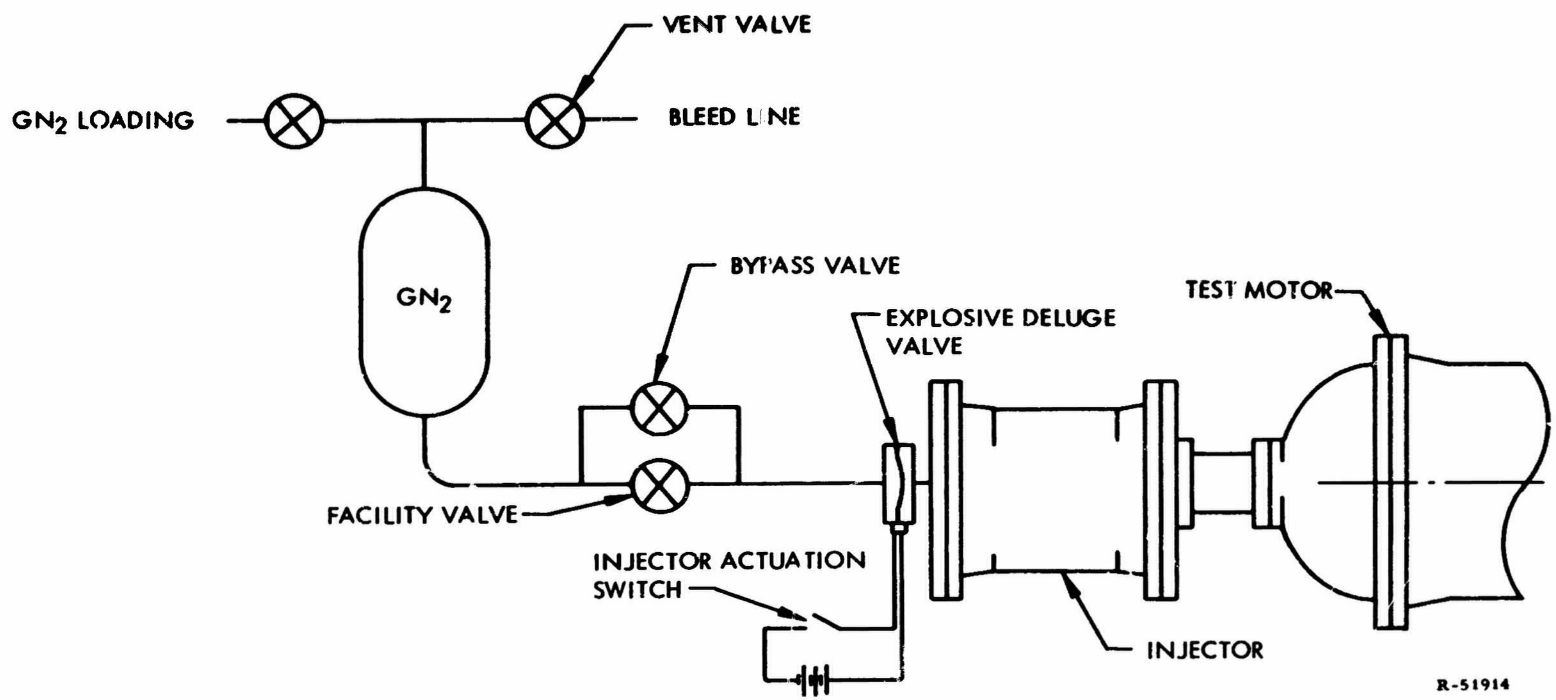


Figure 35. Schematic of the TM-3A Injection System

Sizing of the injector was based on the design parameters curve established by the TM-1 tests and presented in figure 29.

In accordance with this curve, a tradeoff can be made between the water flow rate and the total quantity of water injected. That is, a given motor can be extinguished with a small quantity of water if this quantity is injected at a high rate, or it can be extinguished with a low water rate if a large quantity of water is injected. A single injector could therefore be designed that would provide the injection requirements for TM-3A motors ranging in size from one to five segments. For example: an injector sized to provide a water flow rate of 300 lb/sec will extinguish a one-segment motor with 16 lb of water and a five-segment motor with 75 lb of water.

The injector was therefore sized to provide a maximum flow rate of 300 lb/sec. In order to allow testing at a variety of flow rates (below 300 lb/sec) and total water combinations, the system was designed to have a maximum water capacity of 200 lb.

3. 2. 2 Instrumentation Description

Each test was instrumented to monitor the primary system driving pressure, injection pressure and motor pressure. Taber transducers were used to monitor all pressures. These transducers are capable of responses of 100 cps, which were established as adequate in the small motor program.

3. 2. 3 Test Description

A total of 6 cold-flow tests and 8 extinguishment tests were conducted utilizing 3 one-segment and 2 two-segment TM-3A motors. One cold flow followed by a maximum of three extinguishment tests were scheduled to be conducted in each motor. However, the failure to extinguish several of the motors reduced the total number of firings. The following paragraphs will describe the tests conducted in each motor and present the results of each test. A tabulated presentation of the test results is shown in table VIII.

Prior to initiating the motor extinguishment series, an open-air injector cold-flow test was conducted to verify the structural integrity of the injector and the injector action and to establish the injector flow pattern and swirl plate orifice flow coefficient.

The test configuration for the cold flow is shown in figure 36. An empty TM-3A forward closure was used to attach the injector to the thrust stand as the injector stand was not designed to withstand the reaction force of the water. The GN_2 line pressure and injection pressure were recorded

TABLE VIII

TM-3A EXTINGUISHM

Test No.	Motor Configuration	Injector Configuration	No. of Segments	Primary Injection W_{inj} lb	$\dot{w}_{inj}$ lb/sec	$(P_c)_{inj}$	$\dot{w}_{motor}$ lb/sec	D_t in.	$\dot{w}_{inj}/\dot{w}_{motor}$
1-1	C00603-01	C00872-01	1	31.65	314	525	39.6	3.84	7.92
2-1	C00603-04	C00872-04	1	145	290	840	49.1	3.39	5.90
2-2	C00603-04	C00872-04	1	116	258	710	43.8	3.39	5.90
2-3	C00603-04	C00872-04	1	116	216	570	32.2	3.39	6.70
3-1	C00603-04	C00872-04	1	116	304	650	46.5	3.84	6.50
3-2	C00603-04	C00872-04	1	89	281	750	43.5	3.34	6.45
4-1	C00603-05	C00872-04	2	214	283	950	71.0	3.84	4.0
5-1	C00603-05	C00872-04	2	214	278	950	71.0	3.84	3.92

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TABLE VIII

EXTINGUISHMENT DATA

jection				Backup Injection					
D_t in.	$\dot{w}_{inj}/\dot{w}_{motor}$	W_{inj}/A_B	dp/dt psi/sec	Injectant Pressure psi	Motor P_c psi	ΔP	W_{inj} lb	$\dot{w}_{inj}$ lb/sec	Remarks
3.84	7.92	0.0175	54,800	---	---	---	---	---	Motor was not extinguished
3.39	5.90	0.072	36,000	---	---	---	---	---	Motor extinguished
3.39	5.90	0.063	25,000	800	50	750	500	190	Motor not extinguished by primary. Extinguished by backup injector
3.39	6.70	0.082	10,500	---	---	---	---	---	Motor extinguished
3.84	6.50	0.058	30,400	---	---	---	---	---	Motor extinguished
3.34	6.45	0.049	10,200	250	200	50	500	48	Motor not extinguished by primary or backup systems. Backup system did not function properly
3.84	4.0	0.077	25,800	1,060	320	740	500	182	Not extinguished by either primary or backup system
3.84	3.92	0.077	19,100	1,020	60	960	500	208	Not extinguished by either primary or backup system.

D

Figure 36. Cold-Flow Test Configuration

on the oscillograph, and movement of the piston with respect to time was monitored by high-speed photographs of a graduated scale attached to the injector pintle. The injection parameters (flow rate and charge weight) were selected to be the same as planned for the first extinguishment test. The water charge weight was 31.65 lb (the stroke was 5.7 in.) and the injection flow rate was 300 lb/sec.

The system operated as designed, proving the mechanical and the structural integrity of the hardware. Visual observation of the cold flow on the television monitor indicated the spray pattern to be excellent.

Water distribution into the forward closure area was particularly good. An abundance of water was noted coming from the thrust termination (TT) ports and rebounding off the inside of the closure. The spray pattern had the appearance of being progressive, i.e., starting in the forward closure with a backflow and then progressing to a forward flow with an included angle of approximately 45°.

Inspection of the test bay immediately after the test revealed that the water had been deflected in both an aft and a radial direction as evidenced by moisture on the test bay walls. Water had also been ejected out of the nozzle end of the test bay in an approximate arc of 45° which extended some 20 to 25 ft beyond the injection face.

Motion pictures of the cold flow showed that large amounts of water were ejected out of the TT ports of the forward motor closure used in the test. The deflector gave a fine, folded-fan pattern to the ejected water. The conical effect of the fan pattern partially blocked the camera coverage of the scale used to monitor the movement of the injector piston. However, it was possible to establish the initial movement of the piston and from this data calculate a flow coefficient, C_D. The piston movement was found to be constant, and a C_D of 0.65 was calculated for the swirl plate.

Review of the recorded pressure data shown in figure 37 revealed there was an initial sharp decay in the injectant pressure which later climbed back to near expected figures. This drop was attributed to the large ullage space on the pressure side of the injector piston. To eliminate this problem in subsequent tests, this ullage space was filled with water.

The motor used in the first extinguishment test, motor No. 1, was designed to provide an exact geometrical subscale of the UTC 1201 motor (one-segment version of the Titan III-C SRM). This motor, designated C00603-01-01 and shown in figure 38, was made up of a forward closure, a single center segment, and an aft closure. The internal grain configuration consisted of an eight-point star in the forward closure, a tapered tube

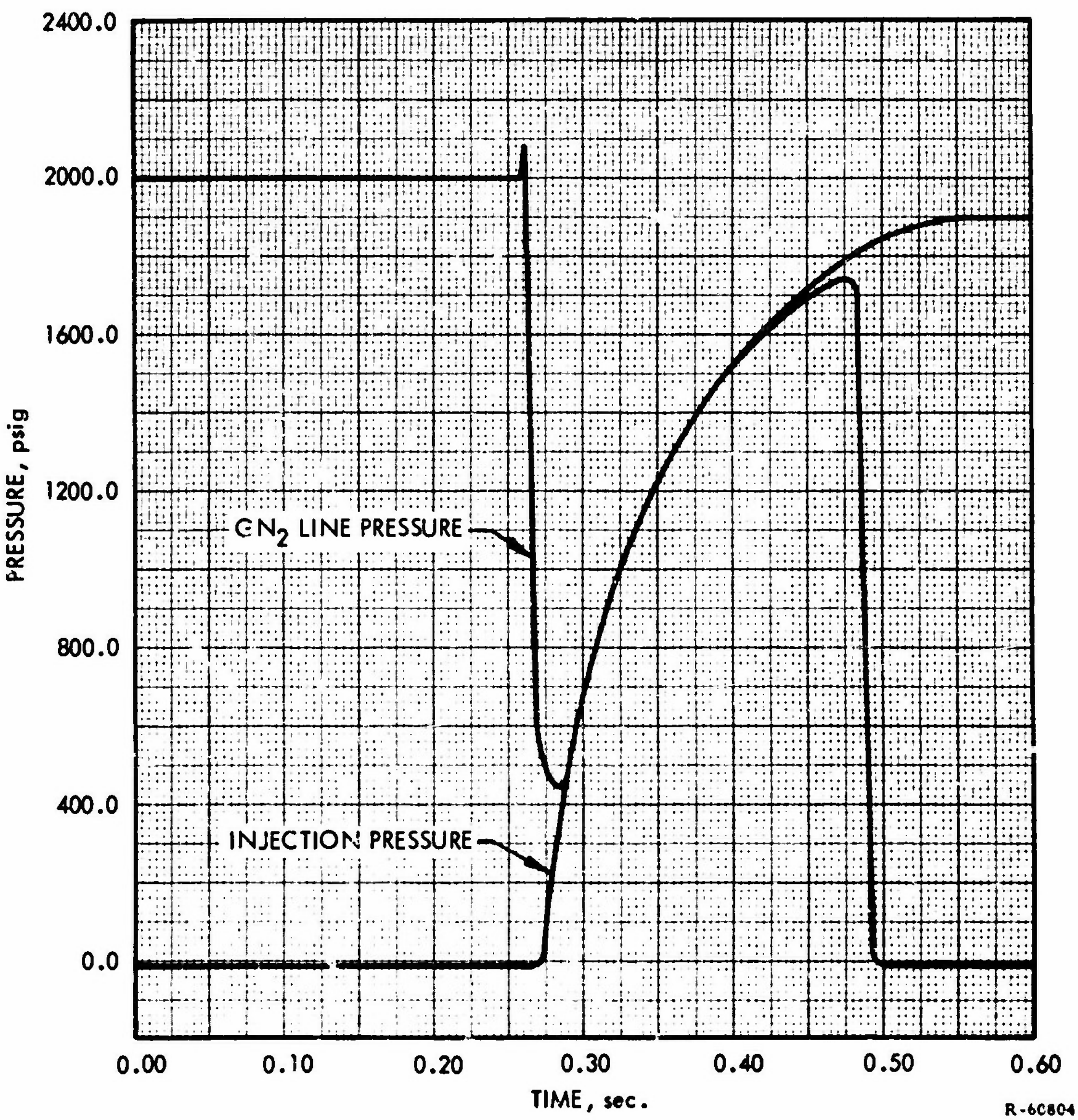
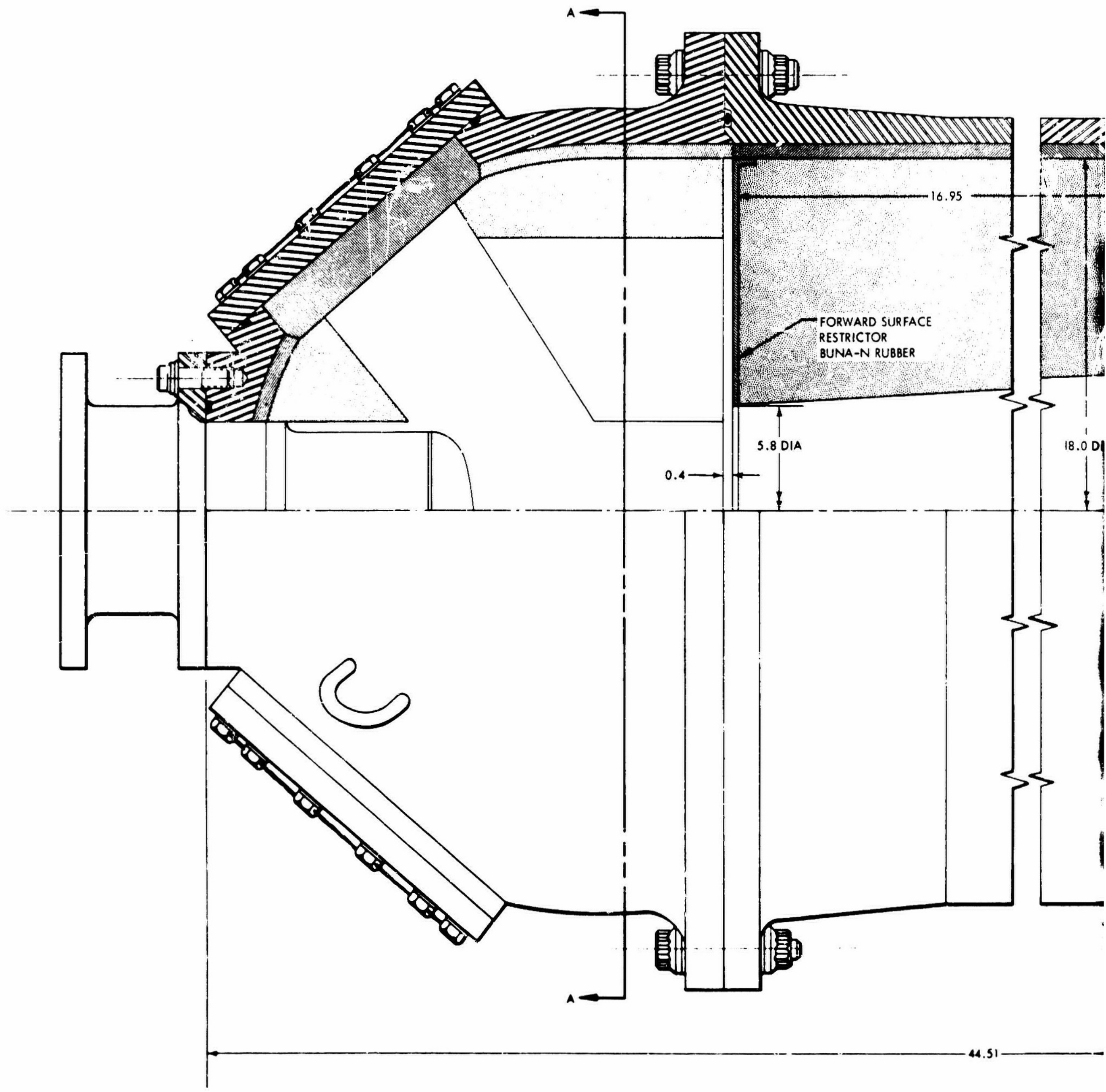


Figure 37. Cold-Flow Pressure vs Time Transient



A
16.95
FORWARD SURFACE
RESTRICTOR
BUNA-N RUBBER
5.8 DIA
0.4
18.0 DI
A
44.51

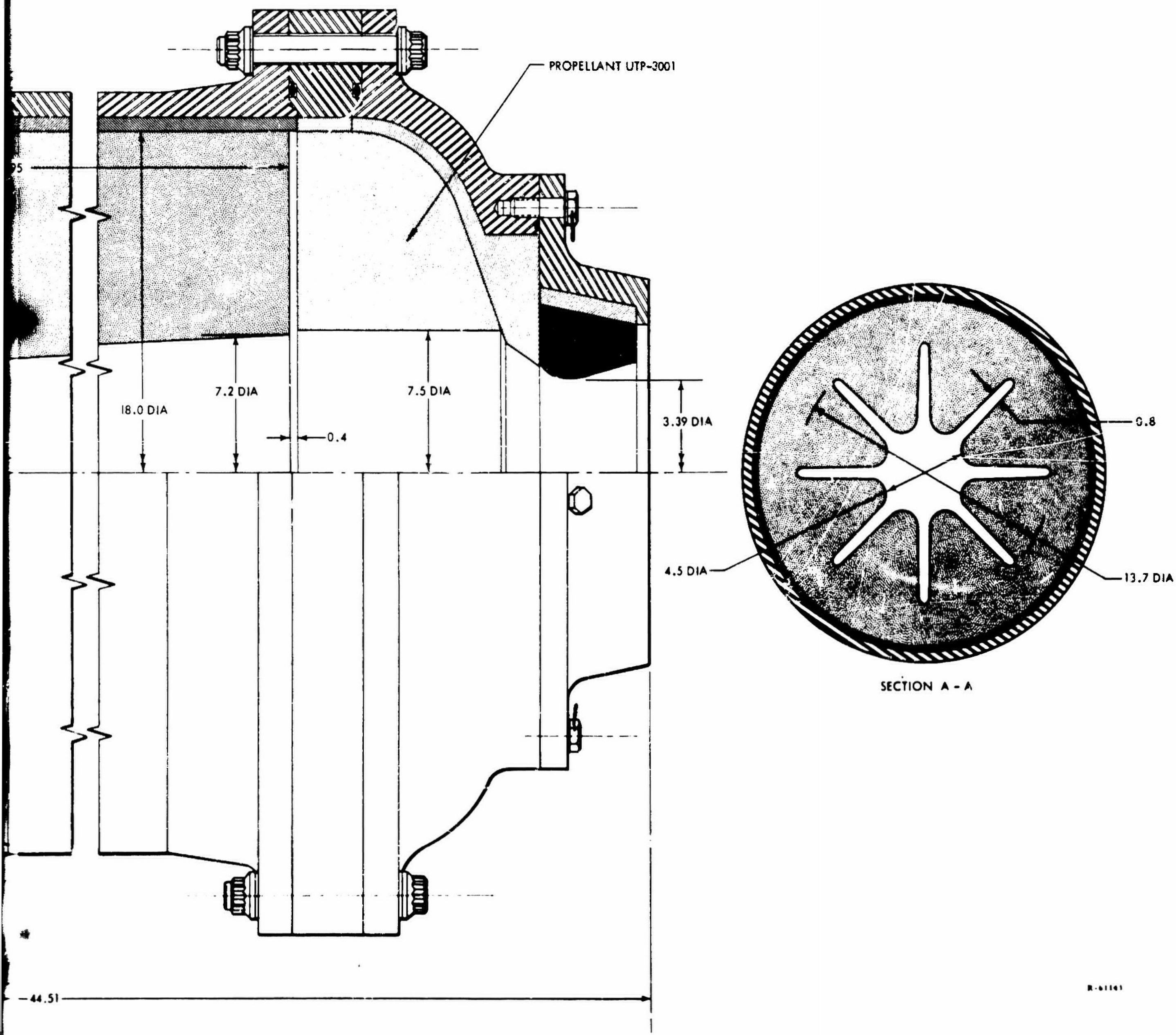


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Figure 38. TM-3A Test Motor, Subscale 1201 Configuration

in the segment, and a cylindrical port in the aft closure. The use of an inhibitor on the forward surface of segment grain produced the motor pressure transient shown in figure 39.

Using the design parameters established in the TM-1 tests as a basis, the design point designated as 1-1 on figure 40 was selected. This resulted in a flow rate of 314 lb/sec and an injection charge weight of 31.65 lb. On the basis of the TM-1 data, these injection quantities provided a safety factor of 2.5 on the water quantity.

Figure 41 shows the position of the deflector plate relative to the propellant surfaces at the time of injection.

The motor was ignited and allowed to burn for 2.0 sec before the injector was actuated. The motor was not extinguished by the injector. Visual observation of the test on the TV monitor indicated that the motor was nearly extinguished by the water, but then reignited. This was verified by the motor pressure versus time data, which showed that the chamber pressure decayed to atmospheric at approximately 0.5 sec after extinguishment (see figures 42 and 43), indicating that most of the propellant had been extinguished. Reignition of all propellant surfaces then occurred, and the motor burned to completion.

In an effort to establish the cause of reignition, an examination was made of the potentially difficult to extinguish areas of the motor. This isolated the aft slot as the probable problem area. The forward closure was disregarded on the basis of the cold-flow test, where large amounts of water were observed to be dispersed into this area. In addition, the aft-slot geometry in this motor is particularly difficult to contact with water because the diameter of the aft closure port is larger than the segment port diameter.

In an effort to verify this assumption, a cold-flow test was conducted to study the water dispersion pattern in a motor of this configuration. To accomplish this, the test was conducted in a live TM-3A motor of the same grain configuration as motor No. 1. The motor was mounted in the test-stand and attached to the injector as shown in figure 44. Spacers were placed between the segment and closure flanges to simulate slot geometry after 2 sec of burnback and to provide an opening in the motor through which the injector flow could be monitored (see figure 45). Plastic bags were attached to the motor at one of the TT ports, the forward slot, and the aft slot to sample a portion of the water injected into these areas.

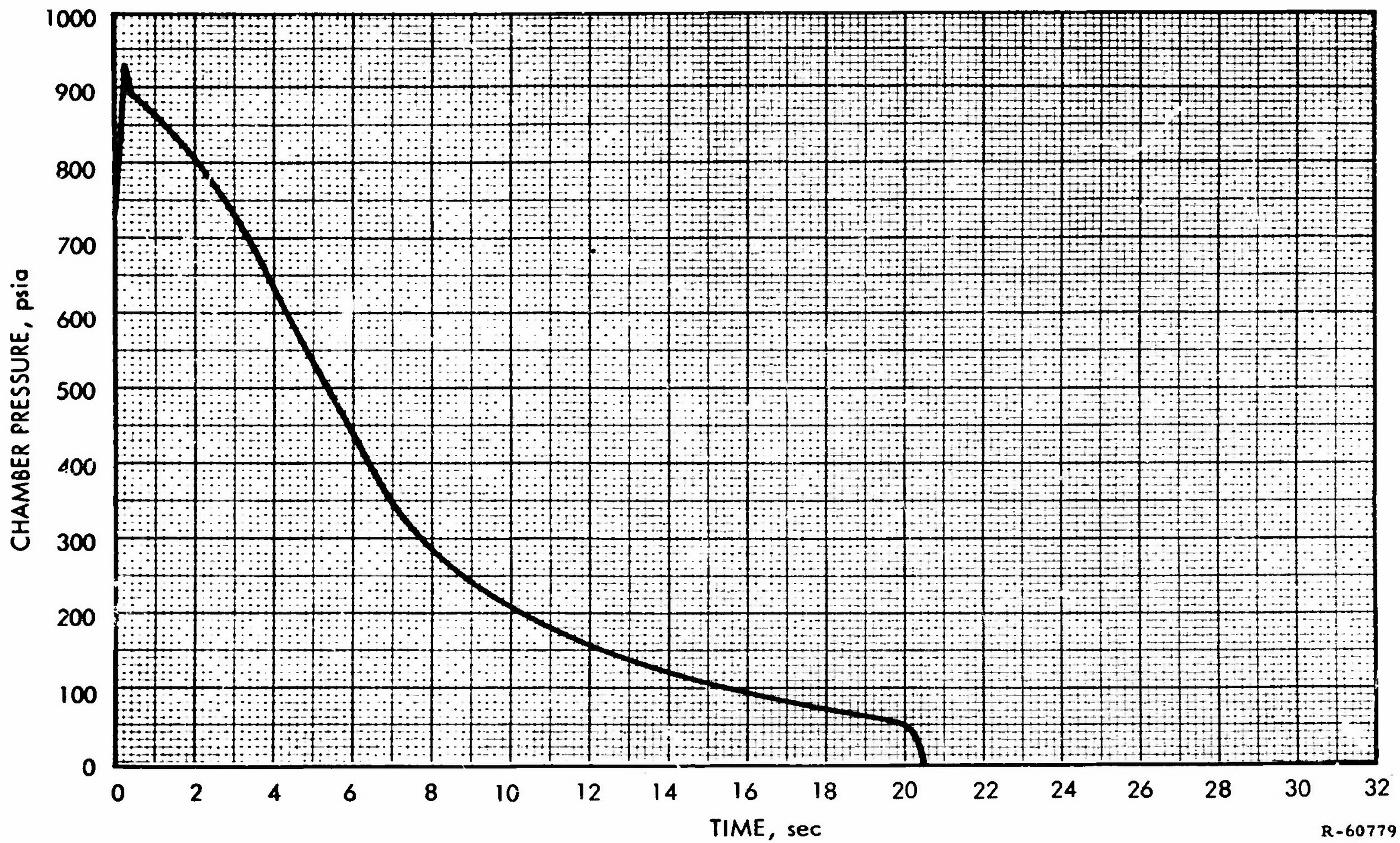


Figure 39. Pressure vs Time Transient, Subscale 1201 Configuration

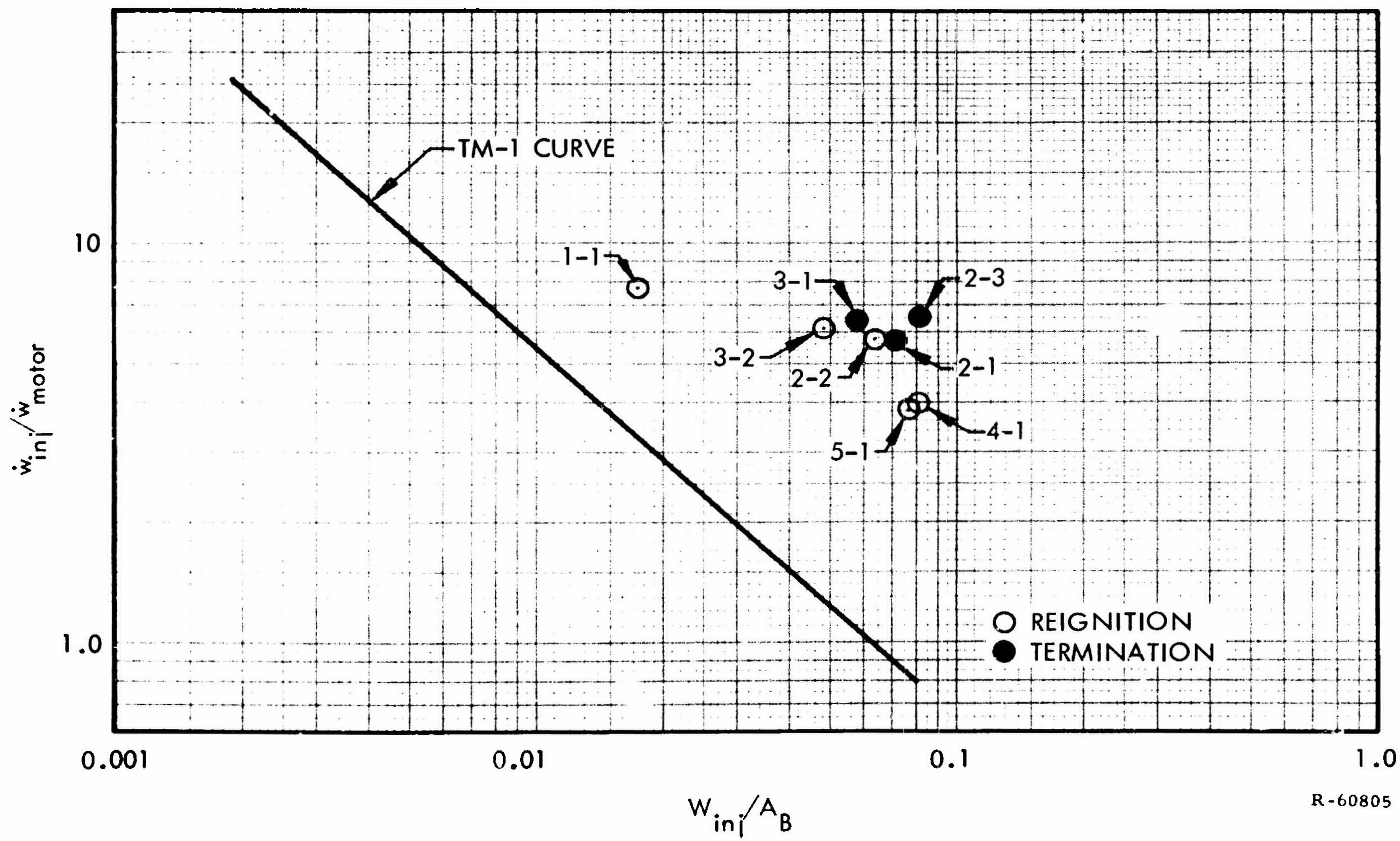


Figure 40. Injection Parameters, TM-3A Tests

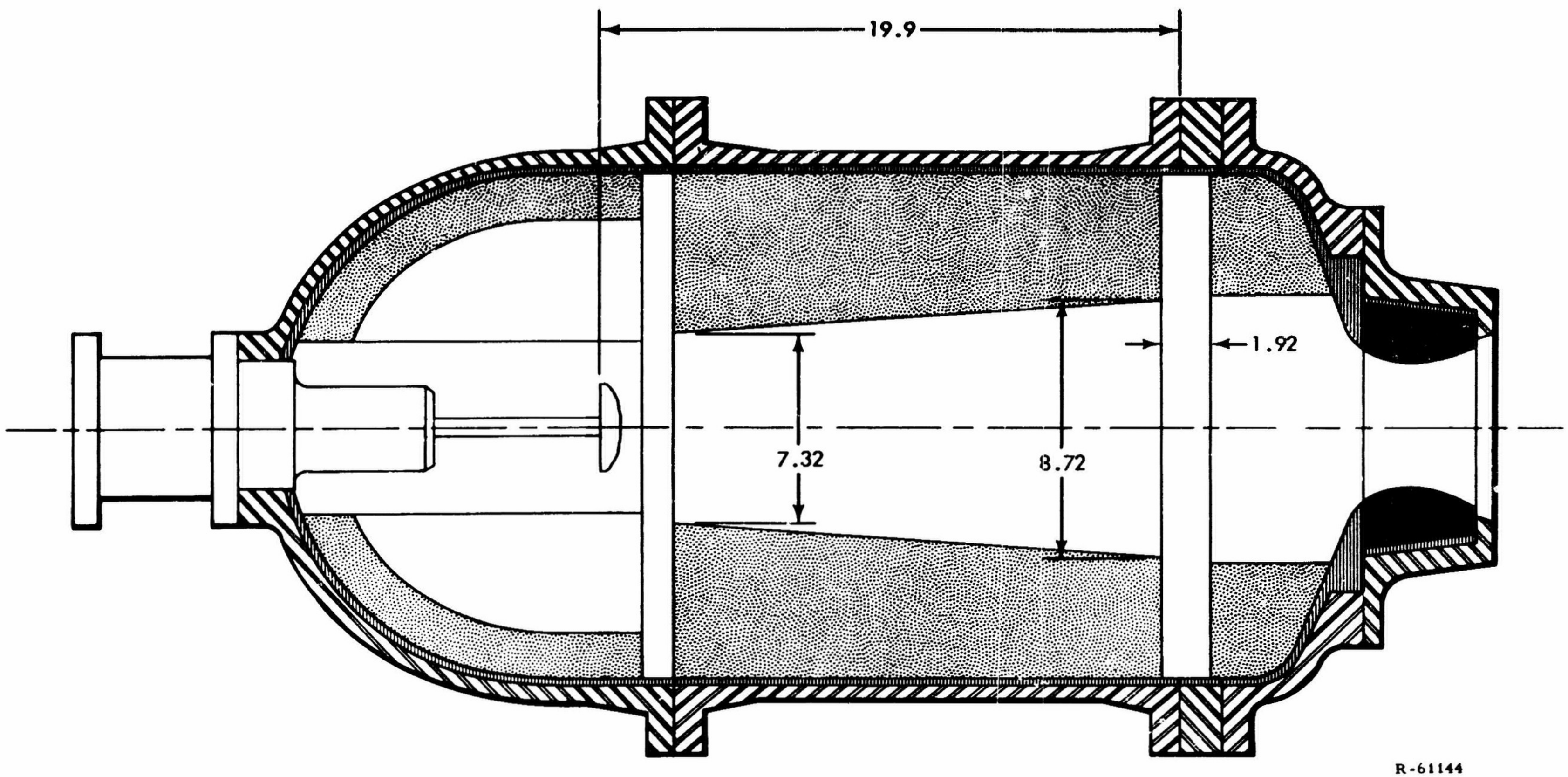


Figure 41. Deflector Position, Relative to Propellant Surfaces at Time of Injection, Test 1-1

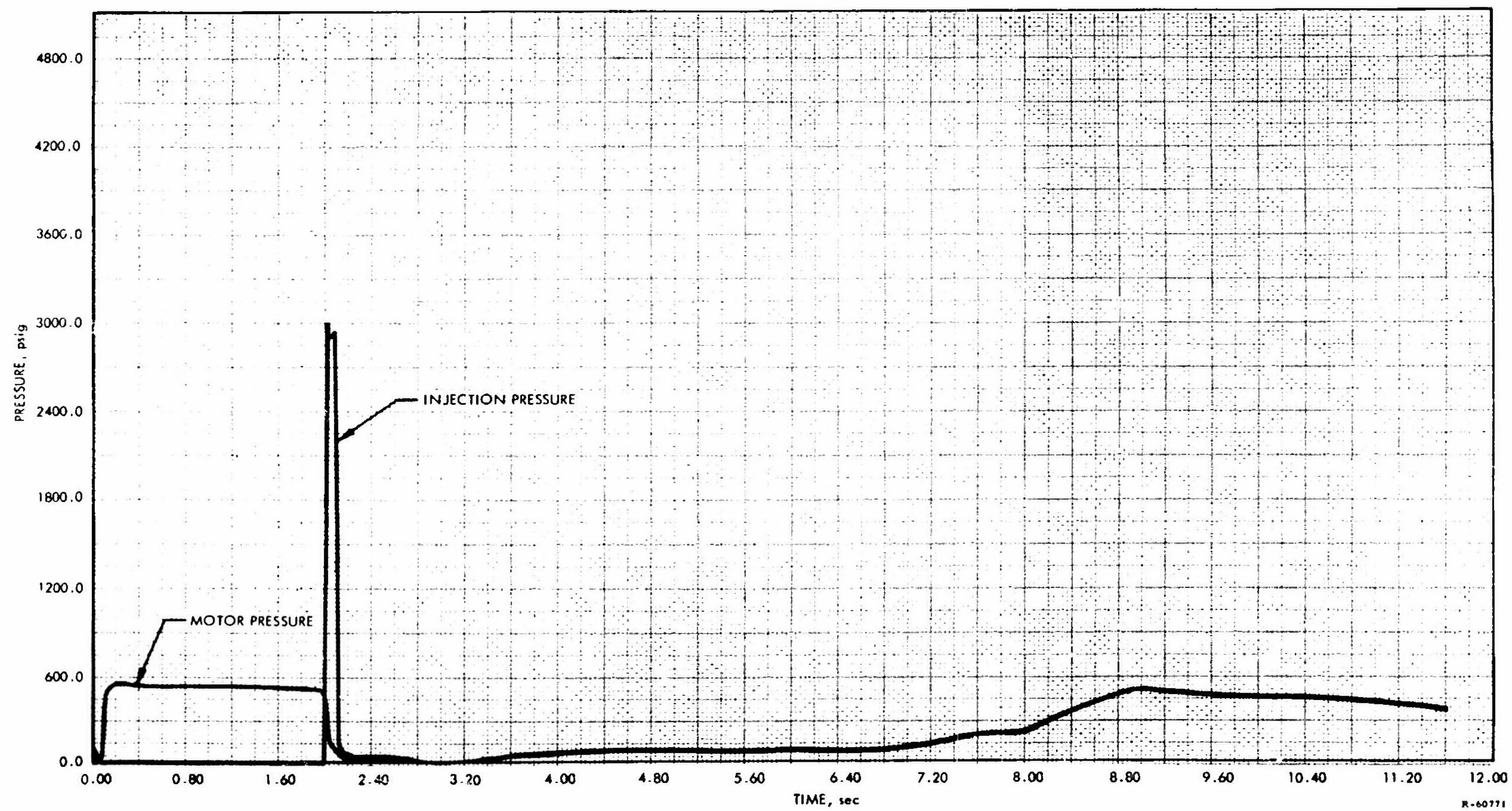


Figure 42. Pressure vs Time Transient, Test 1-1

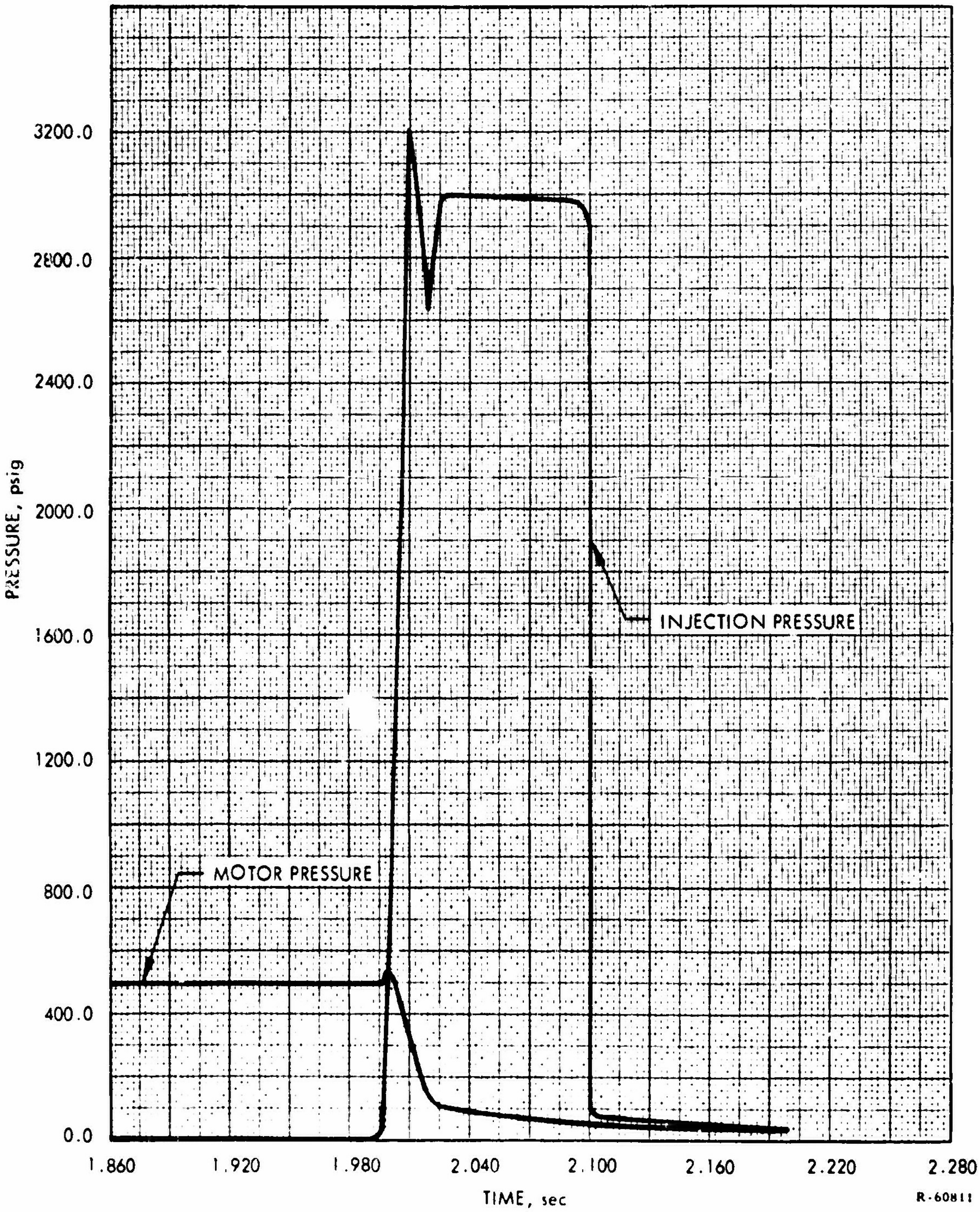


Figure 43. Pressure vs Time Transient, Test 1-1

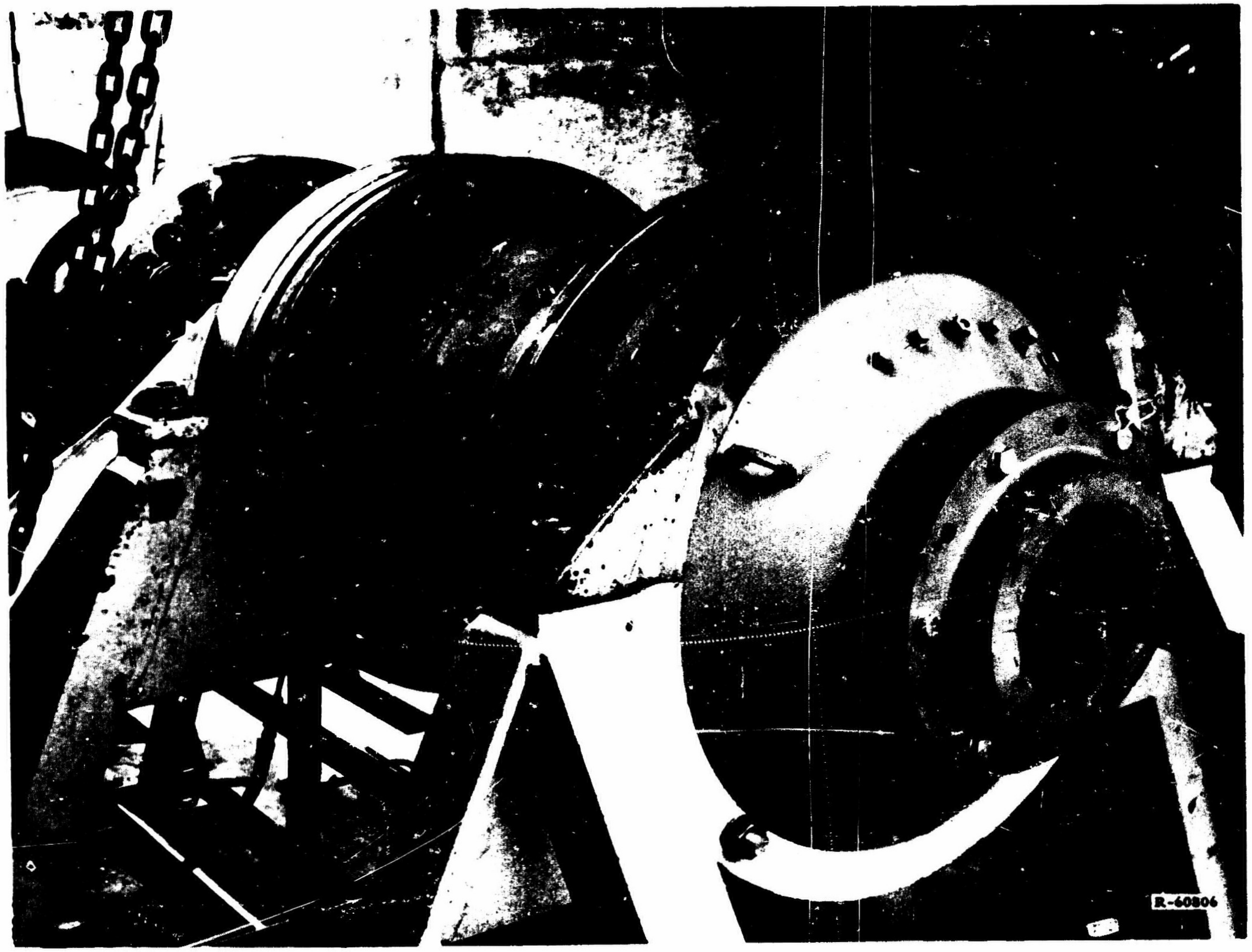


Figure 44. Cold-Flow Test Configuration

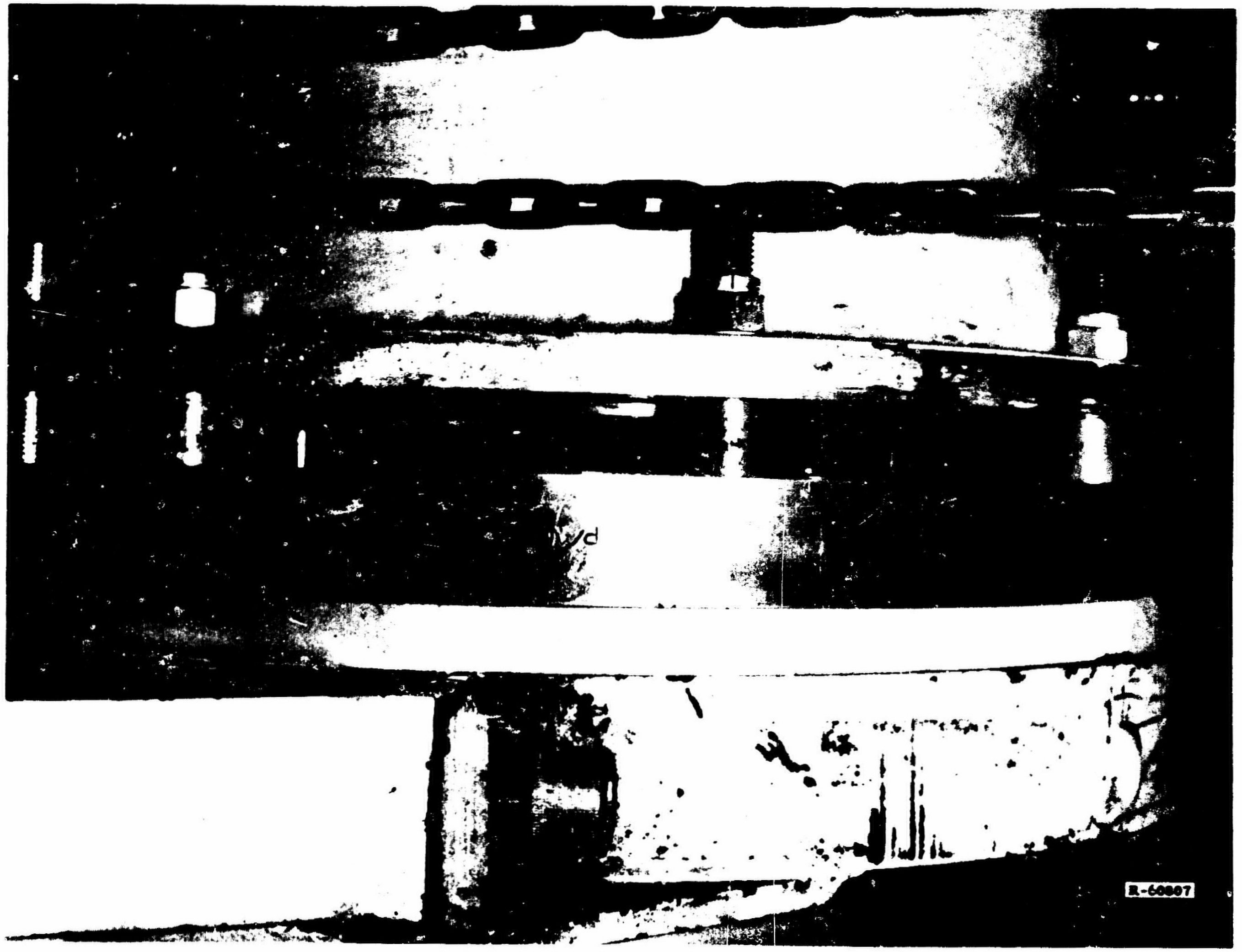


Figure 45. Cold-Flow Test Configuration Showing Aft Slot

To verify earlier C_D calculations, a positive means of monitoring the piston movement was employed. This consisted of a rod attached to the pintle which incorporated the ramp and linear potentiometer shown in figure 46. Movement of the rod actuated the linear potentiometer, which in conjunction with an oscillograph provided a piston travel versus time record.

The injection quantities were nearly the maximum available from the injector. The GN_2 pressure was set at 2,300 psi to simulate the ΔP actually experienced in a motor firing. The piston stroke was set at 26 in. With this stroke, the injector had a water capacity of 145 lb.

Actuation of the deluge valve resulted in a normal response from the injector. Visual observation of the test on the television monitor revealed a large quantity of water being ejected from the forward slot, TT ports, and nozzle. This water obscured the view of the aft slot area to the point that no information was gained on the flow into the aft slot.

Posttest inspection revealed that the plastic bag over the TT port had been badly torn by the high-pressure water stream. The bag at the forward slot was punctured but still contained a considerable quantity of water. The plastic bag at the aft slot was not damaged and contained only a negligible amount of water. Actual measurements indicated that 3 g of water were collected. High-speed motion pictures of the test verified the results indicated by the plastic bags. The film showed that considerable amounts of water were ejected from the TT port, forward slot, and nozzle. However, there was no evidence of water being ejected through the aft slot.

Piston travel as function of time was recorded, and it was established that the piston velocity was constant throughout the test. The calculation of the injector flow coefficient verified the previously calculated C_D of 0.65.

As a result of this test, it was concluded that the aft slot was the probable area of reignition on the first extinguishment test and that all future work should be directed toward improving dispersion into this area and/or determining the effect of slot configuration on motor extinguishment. At this point, extinguishment of slots five-segments downstream of the injector also appeared overly optimistic. On this basis, the program was redirected through a supplemental agreement to the contract (No. 2) to allow changes to the aft slot configuration and to eliminate the requirement for extinguishment tests in five-segment motors. Therefore, the following changes were made to the motor configuration and the injector as a result of this contract change.

A. The motor segment configuration was modified by machining the port to a tube 7.5 in. in diameter (the same diameter

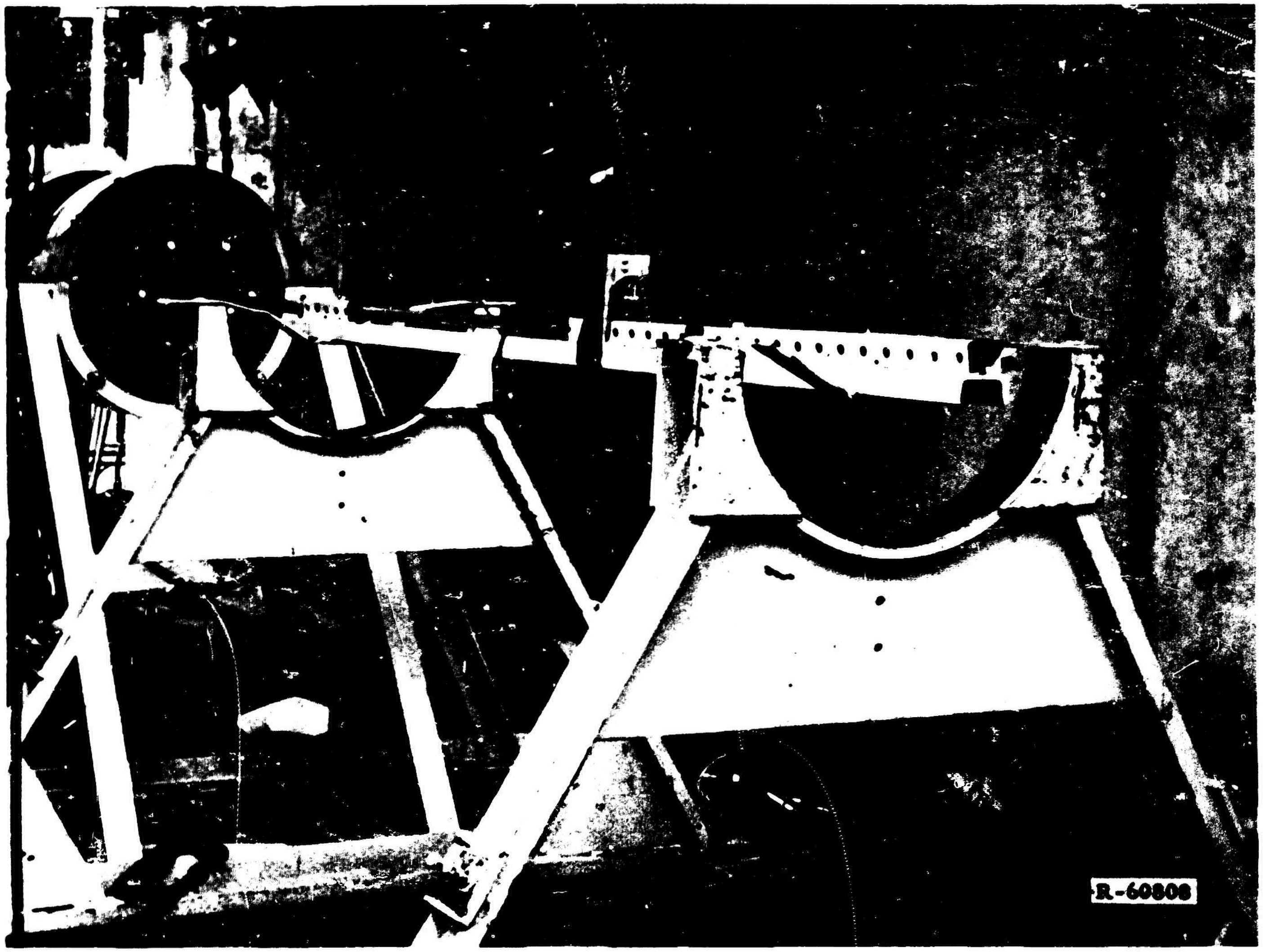


Figure 46. Cold-Flow Test Configuration Showing Piston Travel Monitoring Device

as the port in the aft closure) and removing the restrictor from the forward face. The motor configuration and predicted pressure transient are shown in figures 47 and 48.

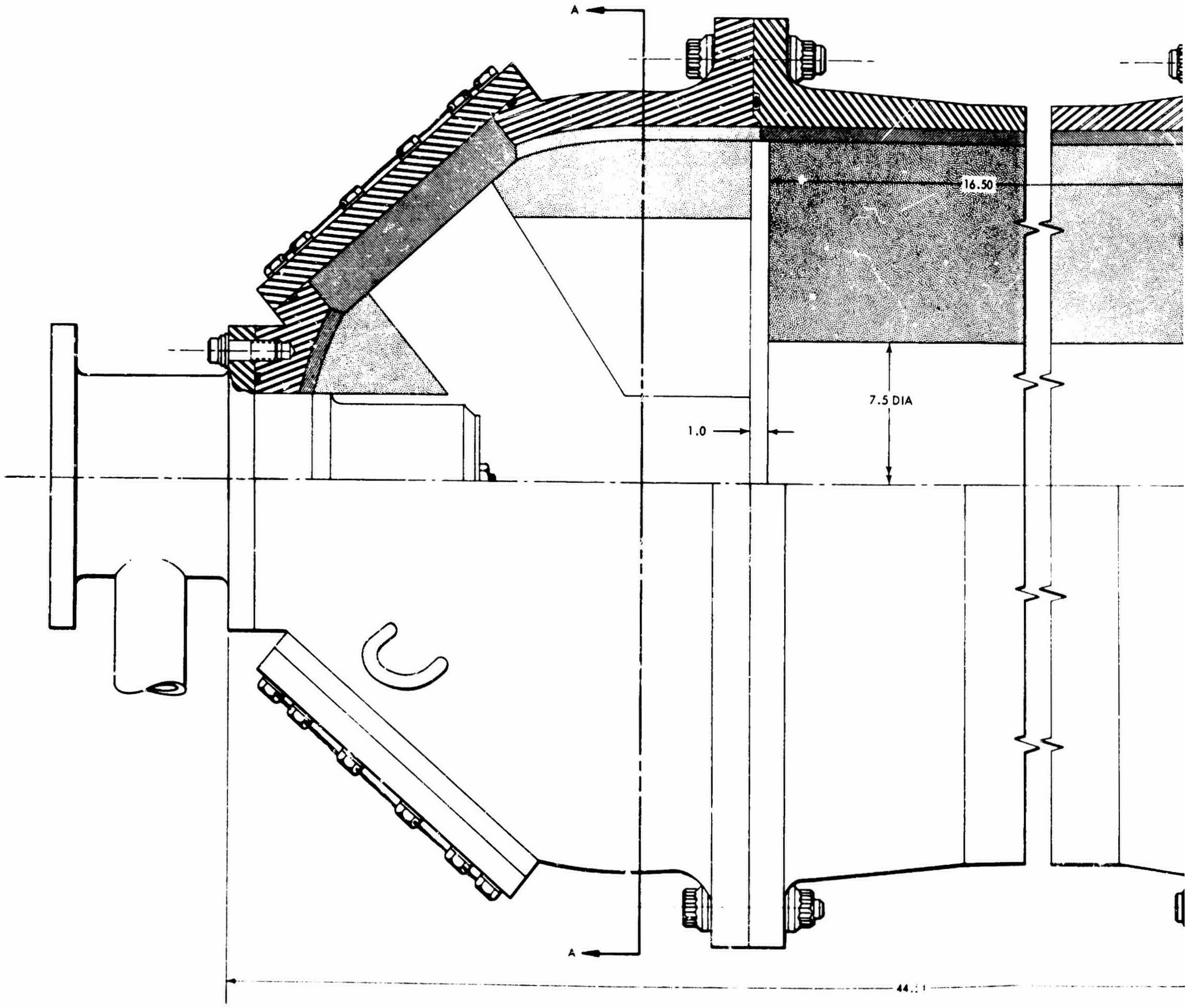
B. The deflector plate of the injector was modified as shown in figure 49 to minimize the restriction of flow downstream toward the aft slot and reduce the quantity of water deflected into the forward closure.

C. The control rod was modified by increasing the thread length at one end. This allowed the stroke length to be varied during the test series with disassembly of the injector.

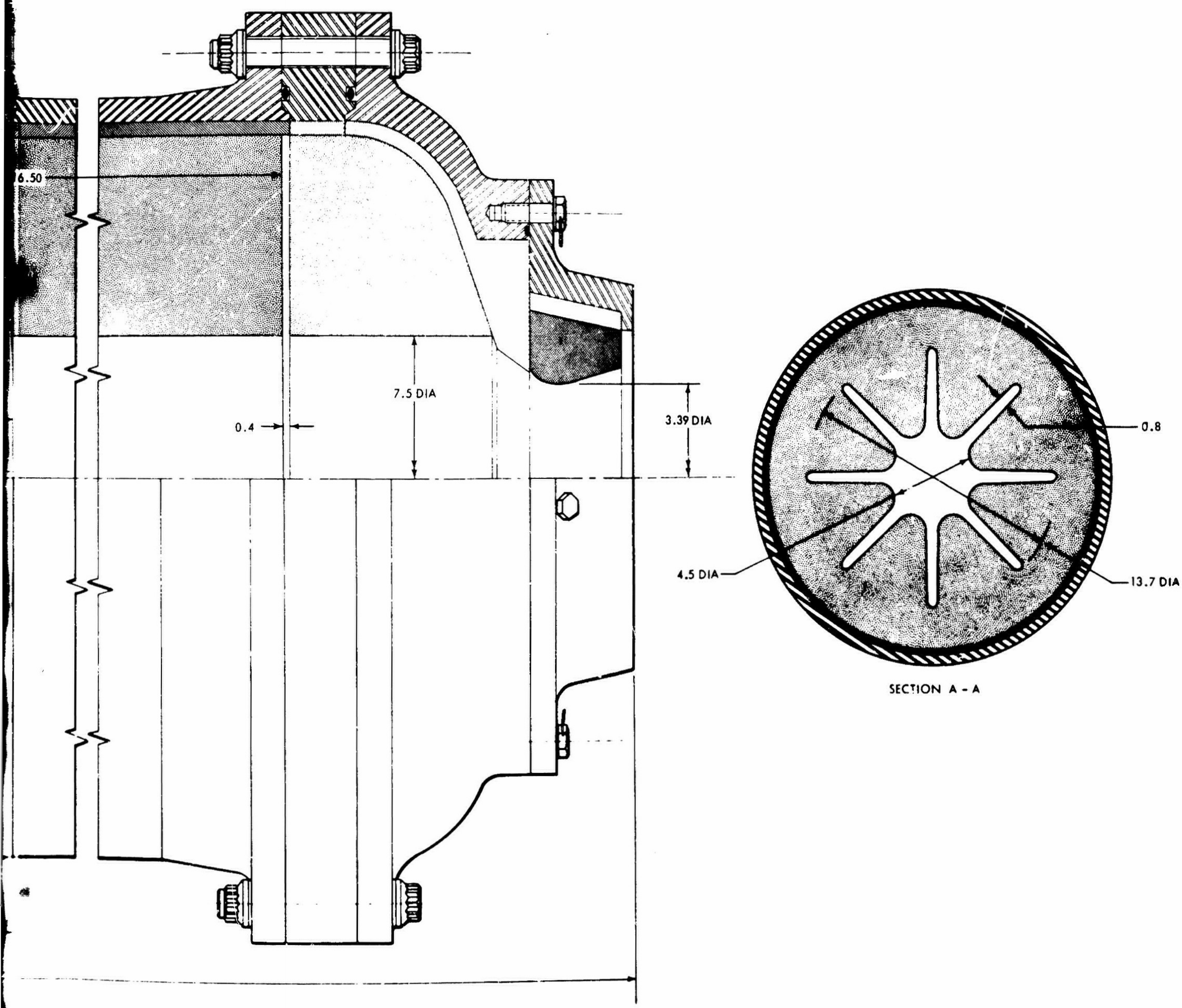
D. A backup injection system was designed and fabricated. The purpose of this system was to ensure extinguishment of the motor in each test and preclude the possibility of a motor reigniting and burning to completion as occurred in motor No. 1. The backup injector consisted of an ullage-pressurized water tank, with a capacity of 500 lb, a GN_2 pressure supply, and a remotely operated actuator valve. A schematic of both the primary and backup injection systems is shown in figure 50.

The water from the backup system was injected into the motor through the primary injector housing; in this manner, the advantage of swirling the water down the port was achieved.

One cold flow was then conducted to verify the structural integrity of the backup system and associated plumbing and to establish the injectant flow pattern in the new motor configuration. To monitor the flow into the aft slot, spacers were again placed between the flanges of the segment and the aft closure and a catcher was located on the aft flange to sample the quantity of water injected into the slot. The exposed frontal area of the catcher covered a 4.0-in. arc length on the motor circumference. The injector control rod was adjusted to provide the maximum piston travel for a one-segment motor. Additional stroke would have caused blockage of the motor throat by the deflector. This resulted in a stroke of 26 in. and an injector capacity of 145 lb. The GN_2 tank was pressurized to 2,200 psi to simulate the ΔP of the proposed motor firing. Actuation of the deluge valve resulted in a normal response by the injector. The structural integrity of the backup injector and all associated plumbing was established. Visual observation of the test on the television monitor indicated improved water dispersion into the aft slot. This was verified by the high-speed



A



B

Figure 47. TM-3A Motor Configuration

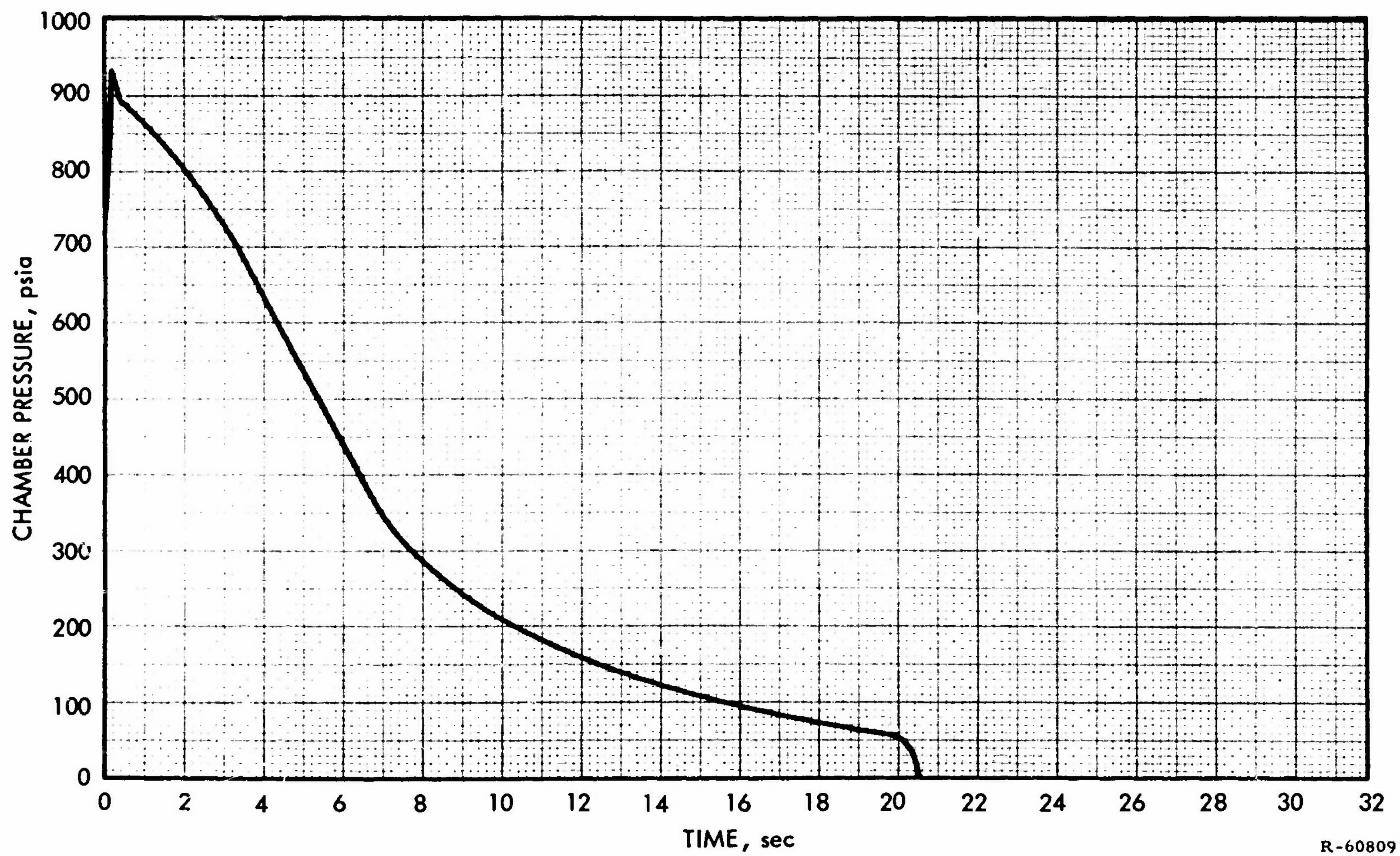


Figure 48. Pressure vs Time Transient TM-3A Motor

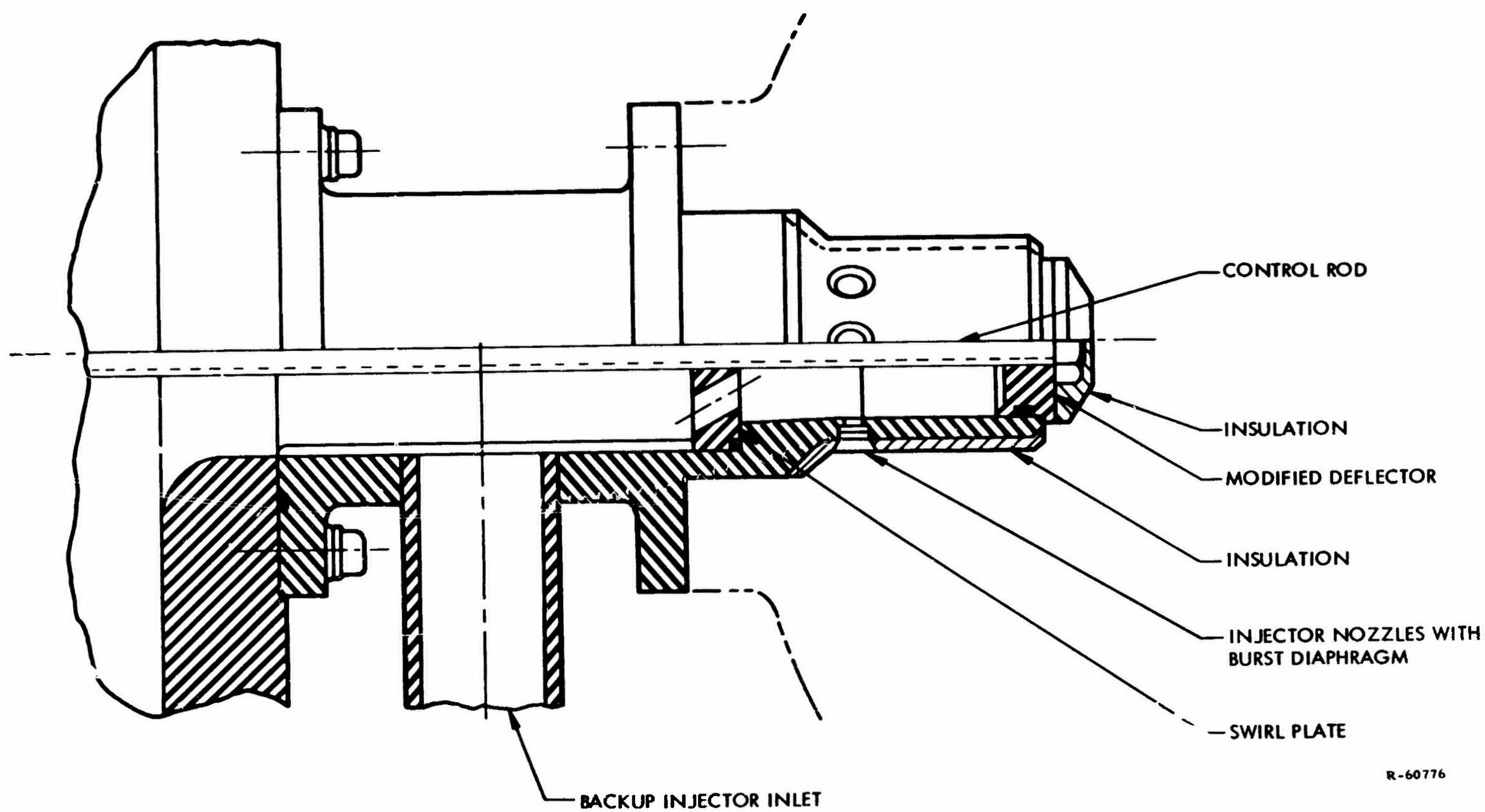


Figure 49. Modified Injector Showing Backup System Inlet

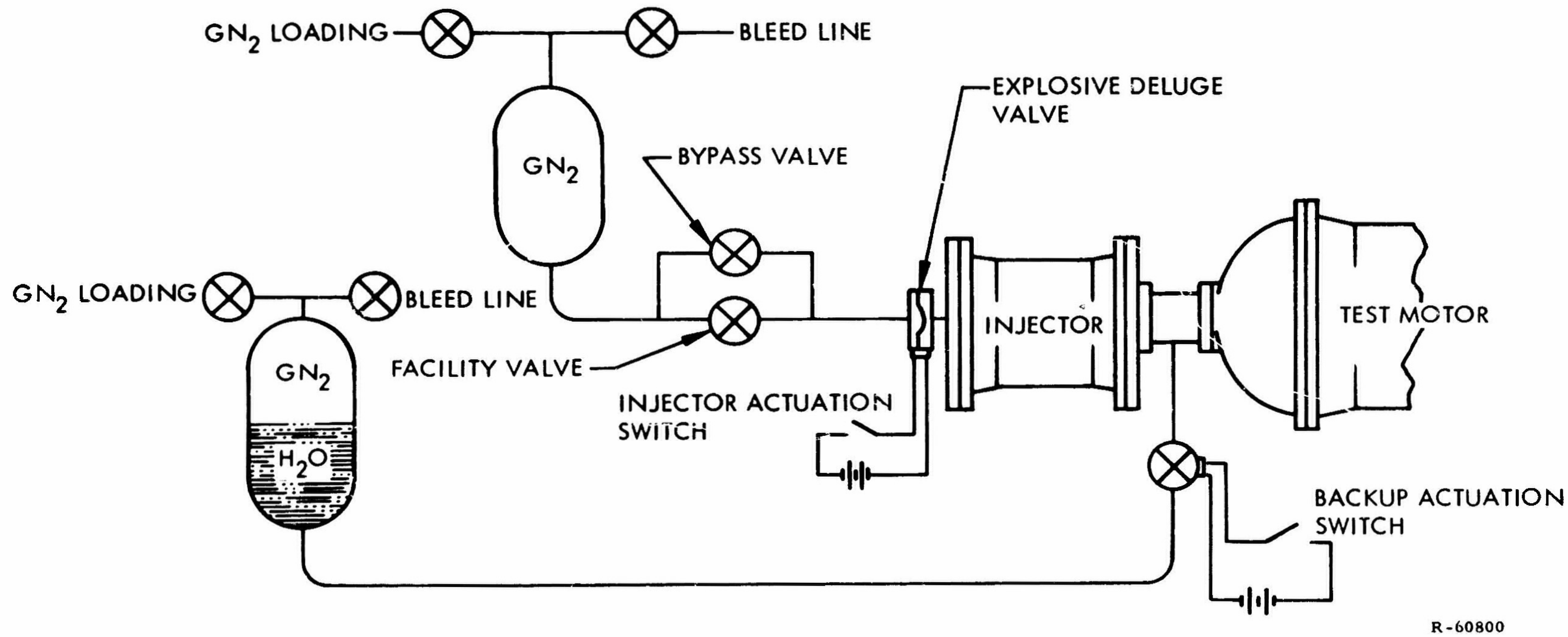


Figure 50. Test Setup Schematic

motion pictures and by posttest inspection which revealed that 1.44 lb of water was collected by the catcher. Assuming uniform flow into the slot over the entire circumference, it can be calculated that a total of 27.4 lb or 19% of water entered the aft slot area. As approximately 20% of the surface area is in the aft slot, uniform coverage of the entire grain surface could be assumed.

On the basis of these results, the first extinguishment test was conducted on this motor. The primary injector was recycled using the same piston travel and injectant quantity as the cold flow. The design point resulting from these injectant quantities is shown as 2-1 in figure 40. Based on the TM-1 data this provided a safety factor of approximately 7.0 on the total water quantity. The position of the deflector plate relative to the propellant surfaces at the time of injection is shown in figure 51. The backup system was loaded with approximately 500 lb of water and pressurized to approximately 1,800 psi. The motor was ignited and allowed to burn for 2 sec before the primary injector was actuated. Visual observation of the test on the television monitor revealed that the motor was extinguished immediately. Posttest examination of the motor revealed uniform burning of the grain with no irregularities on the grain surface. The pressure versus time transients of the extinguishment are shown in figures 52 and 53.

The motor was then prepared for a second test to establish the effect, if any, of the deflector position with respect to the aft slot. All excess water was drained from the motor, and the propellant surface was wiped dry and then purged with dry nitrogen. The injector was refurbished, and the control rod was adjusted to provide a piston travel of 21 in. This resulted in an injectant charge weight of 115 lb. The GN_2 tank pressure was set to provide a flow rate of 285 lb/sec. Considering the burnback of the propellant grain, these injection parameters provided a design point very near the design point of the previous test (see point 2-2 on figure 40). The primary difference between the two tests was therefore limited to the deflector action and the effect of deflector position on extinguishment. In the first test, the deflector moved to a position approximately opposite to the slot, while on this test the deflector was located upstream of the aft surface of the segment grain at the time of injection, as shown in figure 54.

The motor was ignited and allowed to burn for 1 sec before the primary injector was actuated. Visual observation of the test on the television monitor indicated that the motor had been extinguished. The exhaust plume collapsed immediately, and there was no smoke or flame evident at the nozzle throat. After approximately 4 sec, the movie cameras were shut down and the oscillograph speed was reduced to 4 in./sec.

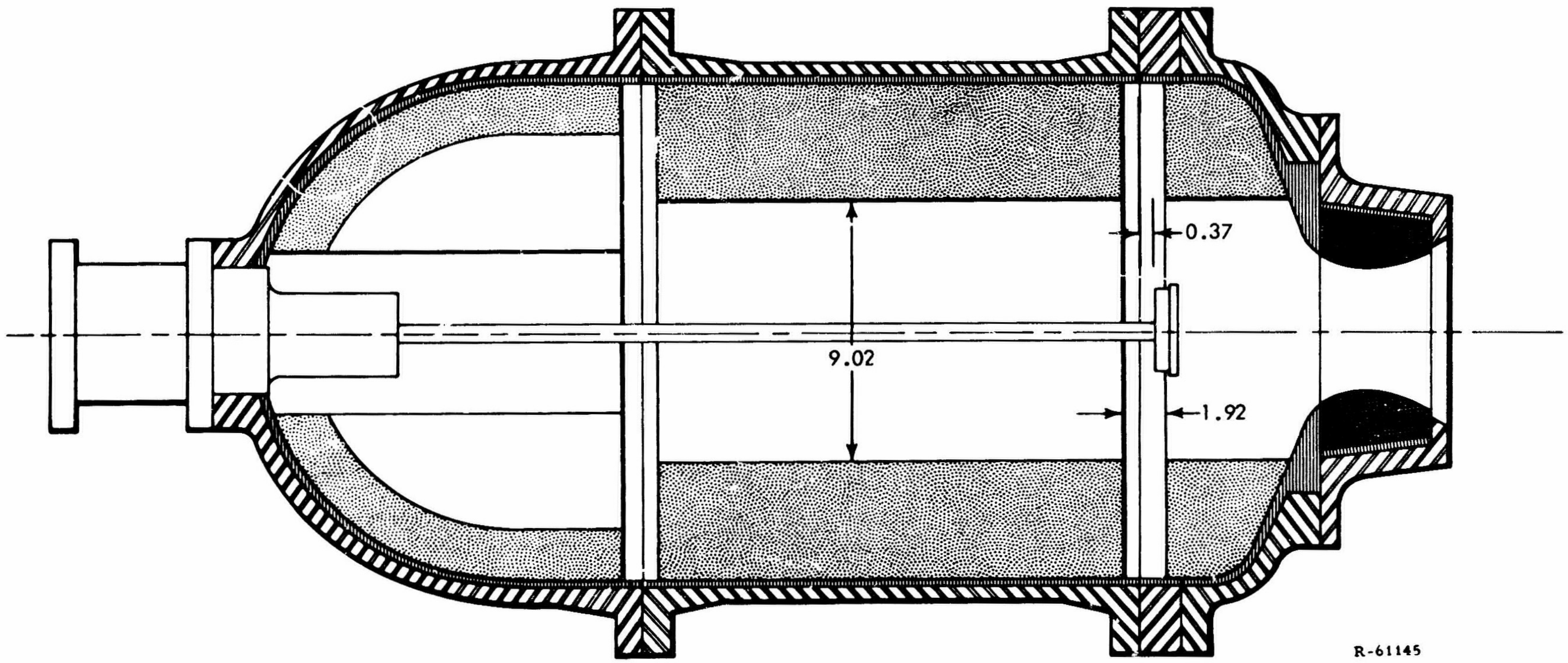


Figure 51. Deflector Position, Relative to Propellant Surfaces at Time of Injection, Test 2-1

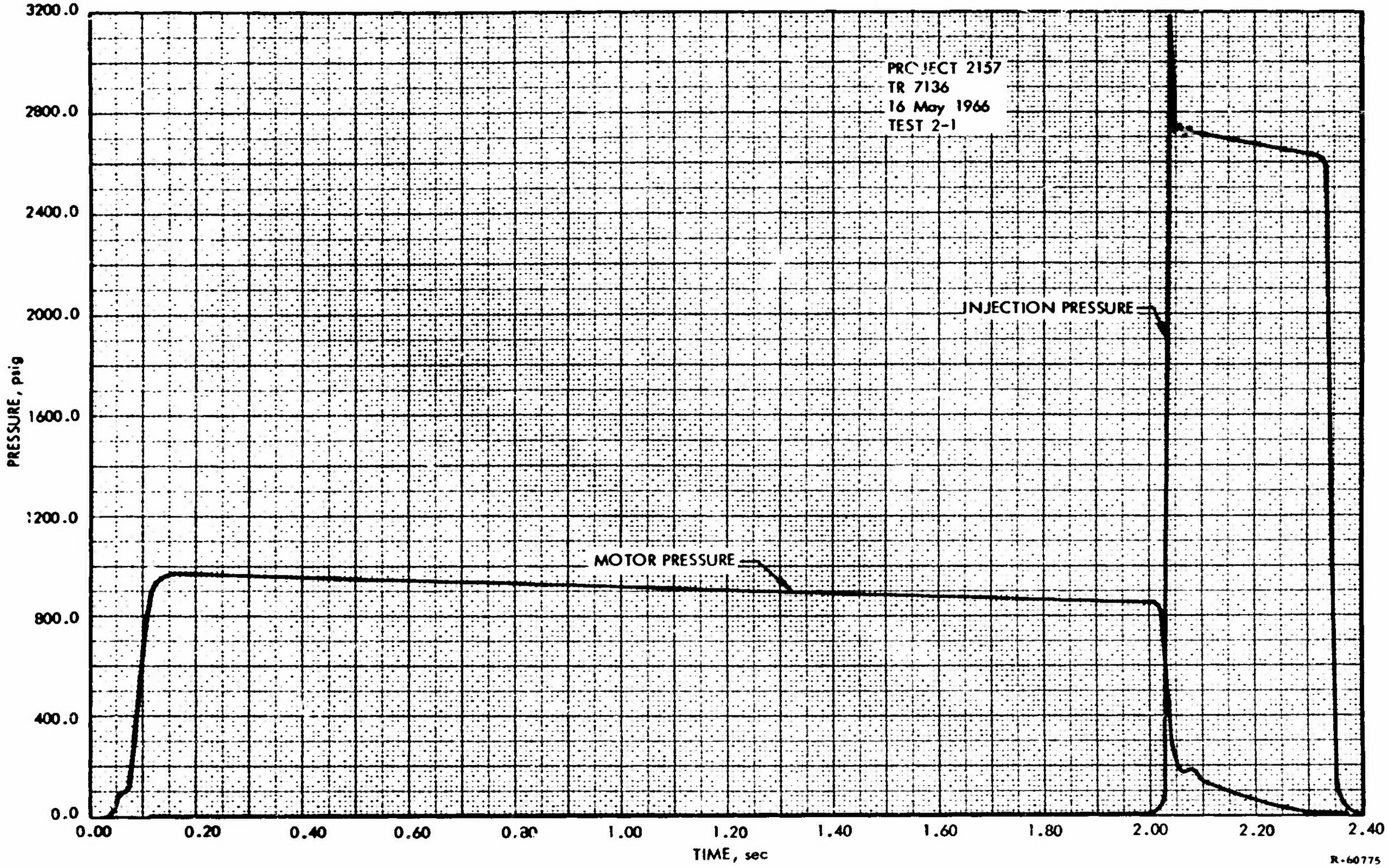


Figure 52. Pressure vs Time Transient, Test 2-1

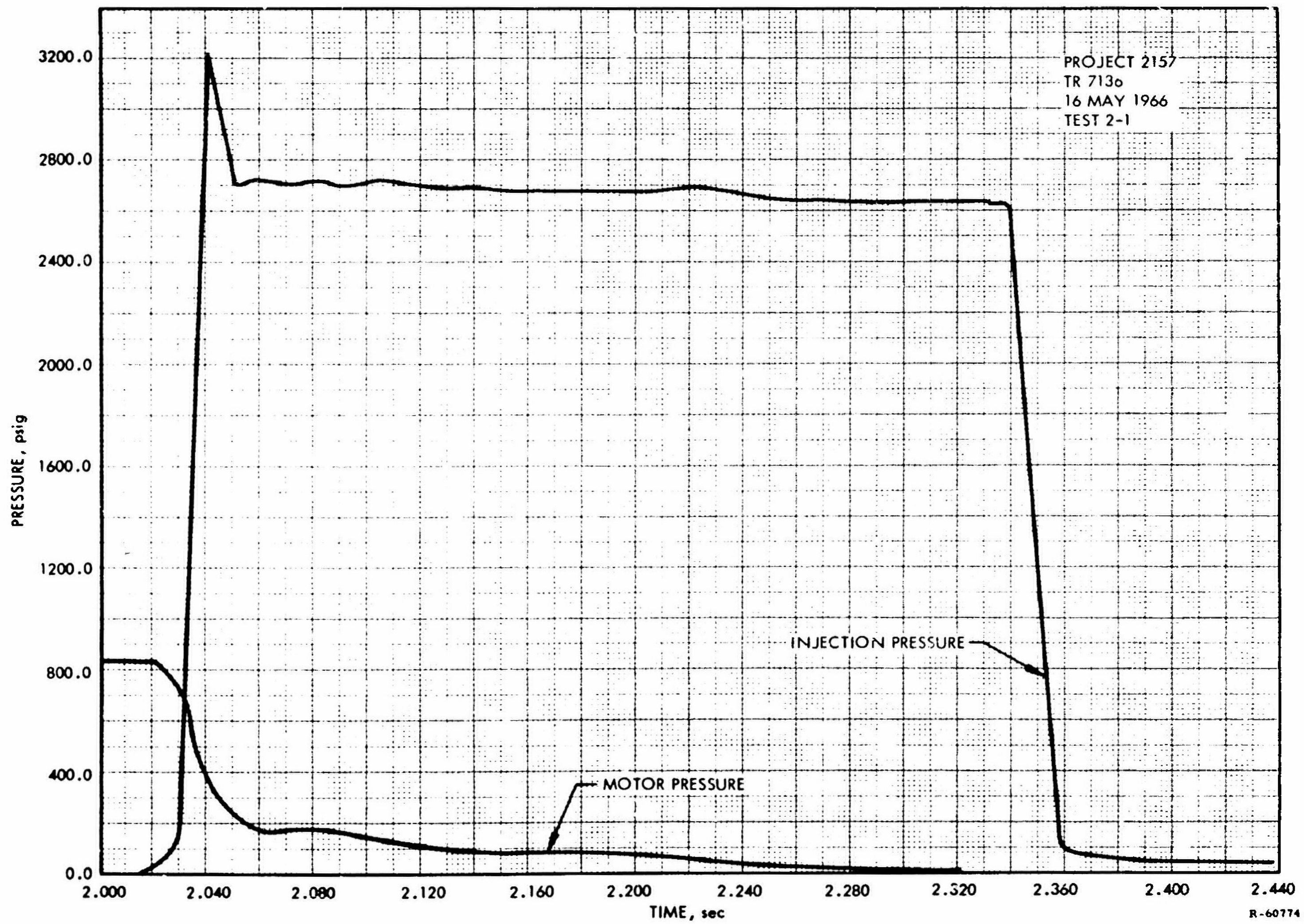


Figure 53. Pressure vs Time Transient, Test 2-1

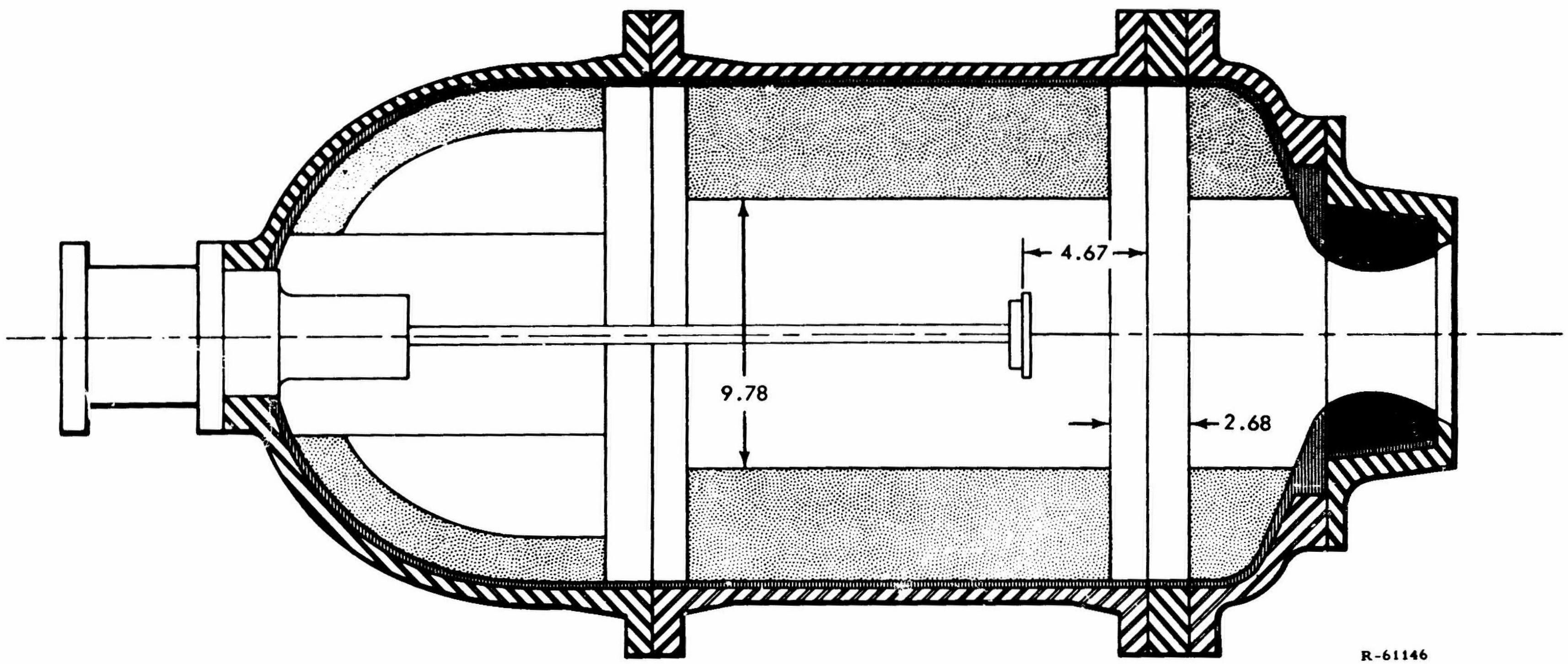


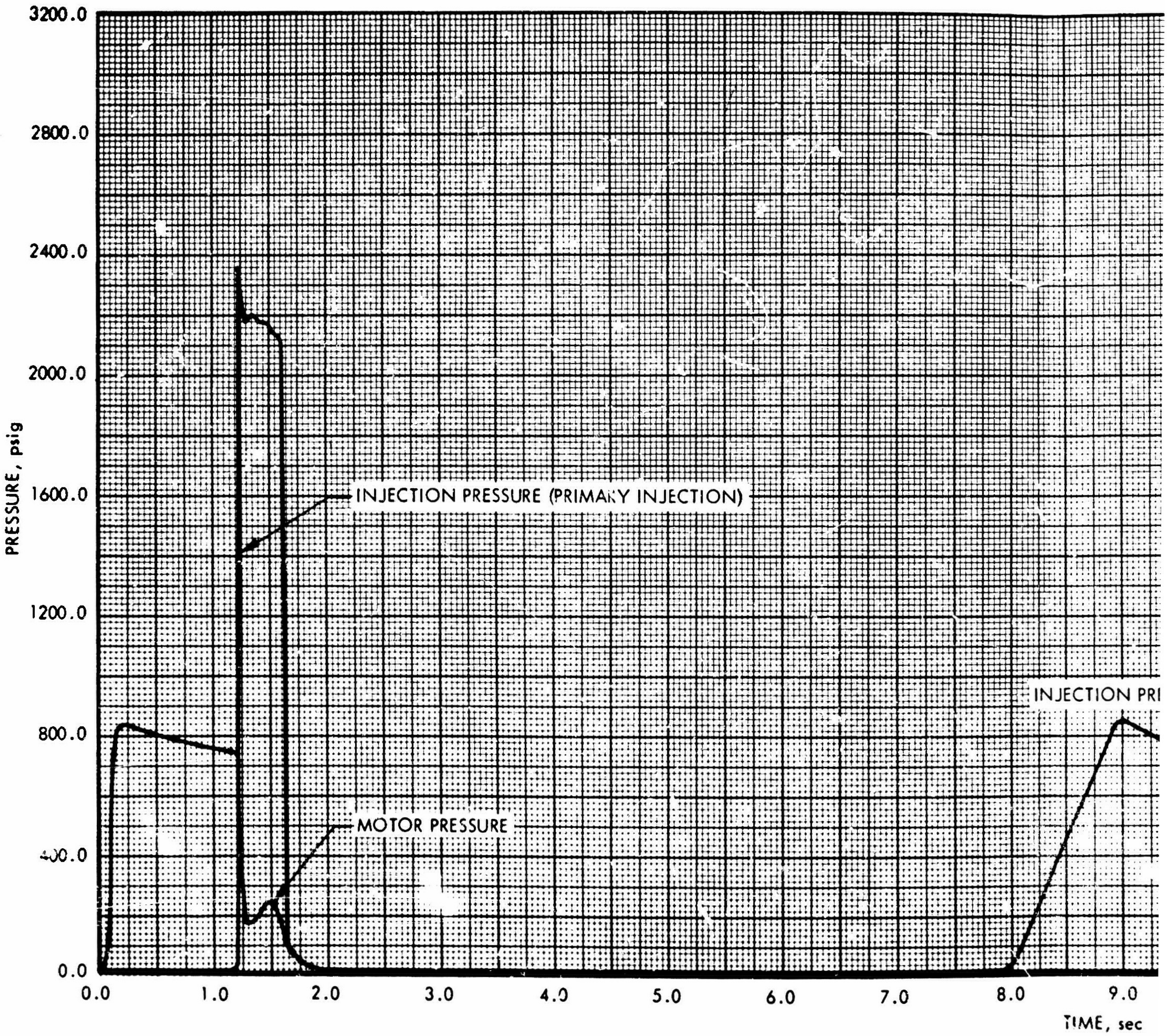
Figure 54. Deflector Position, Relative to the Propellant Surface at Time of Injection, Test 2-2

After approximately 7 sec, a wisp of smoke appeared in the motor nozzle, and in the next few milliseconds the smoke increased and a flame was evident. At this time, the backup system was actuated and a second charge of water was injected through the motor. This time the motor was extinguished immediately and did not reignite. The pressure versus time transient shown in figures 55 and 56 clearly shows the period where there was no appreciable burning in the motor chamber.

Posttest inspection of the motor indicated that reignition had taken place in the aft slot area. While the motor was not disassembled, it was possible to feel the surface of the propellant in both the port and the slot area. Two small potholes, indicating point burning, were discovered on the aft surface of the segment propellant. These potholes were hemispherical in shape and similar to the holes caused by point burning in laboratory tests No. 001, 002, and 003 shown in figure 8. One, located at 1:00, was approximately 1 in. in diameter and 3/8 in. deep; the other, located at 2:00 near the segment insulation, was hemispherical and approximately 3/4 in. in diameter. The upper portion of the propellant in the aft closure had an appearance of being either burned or eroded. This condition was evident only in the upper portion of the port and covered an arc of approximately 120°. The surface propellant in this area had been eroded to a depth of about one-tenth of an inch, indicating either burning or the passing of hot gases over this area. It is reasonable to assume that if the motor had been reignited from spots of point burning in the upper portion of the slot, the spread of the flame front would follow the flow of combustion gases over the area in the upper portion of the aft closure and cause the surface condition that was evident.

Preparations were then made for a third extinguishment test using this motor. All excess water was drained from the motor, and the propellant surfaces were wiped dry and then purged with dry nitrogen. The injector was refurbished and charged with water. Because the previous test had not successfully terminated combustion, the injector piston stroke and charge weight was not changed so that conditions of the previous test could be duplicated as closely as possible. The injection pressure was reduced from the previous test to provide the injection required by the lower motor propellant mass flow. By duplicating the design parameters of the previous test, the effect of the deflector location relative to the aft slot could be further evaluated. Burnback of the propellant surfaces, both in the slot and the port, significantly influence the ability to inject water into the slot. The position of the deflector relative to the propellant surfaces at the time of injection is shown in figure 57.

Both the primary and backup systems were charged with water and pressurized. The motor was ignited and allowed to burn for 1.0 sec before


3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
PRESSURE, psig
INJECTION PRESSURE (PRIMARY INJECTION)
MOTOR PRESSURE
INJECTION PRI
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
TIME, sec

77

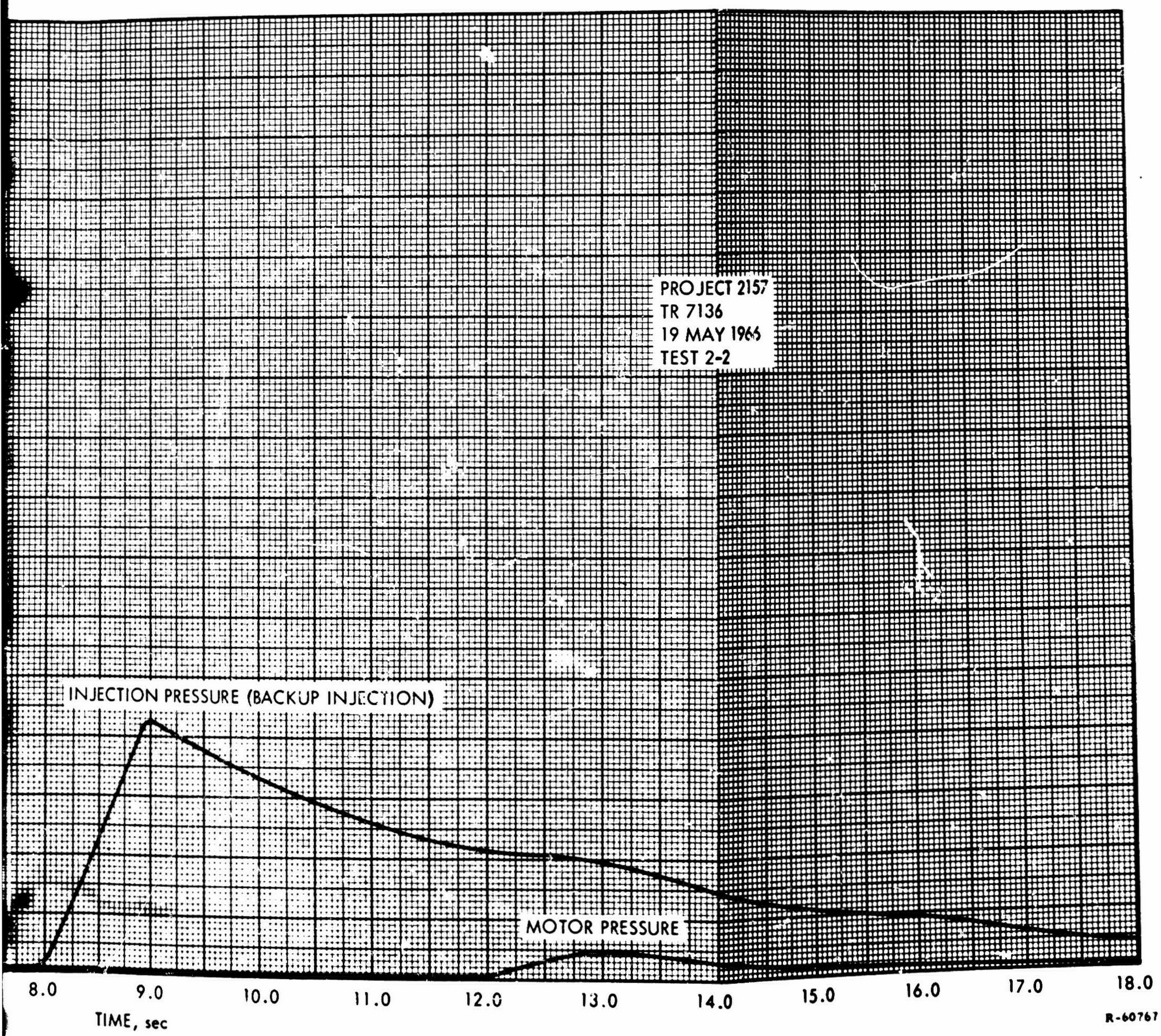


Figure 55. Pressure vs Time Transient, Test 2-2

B

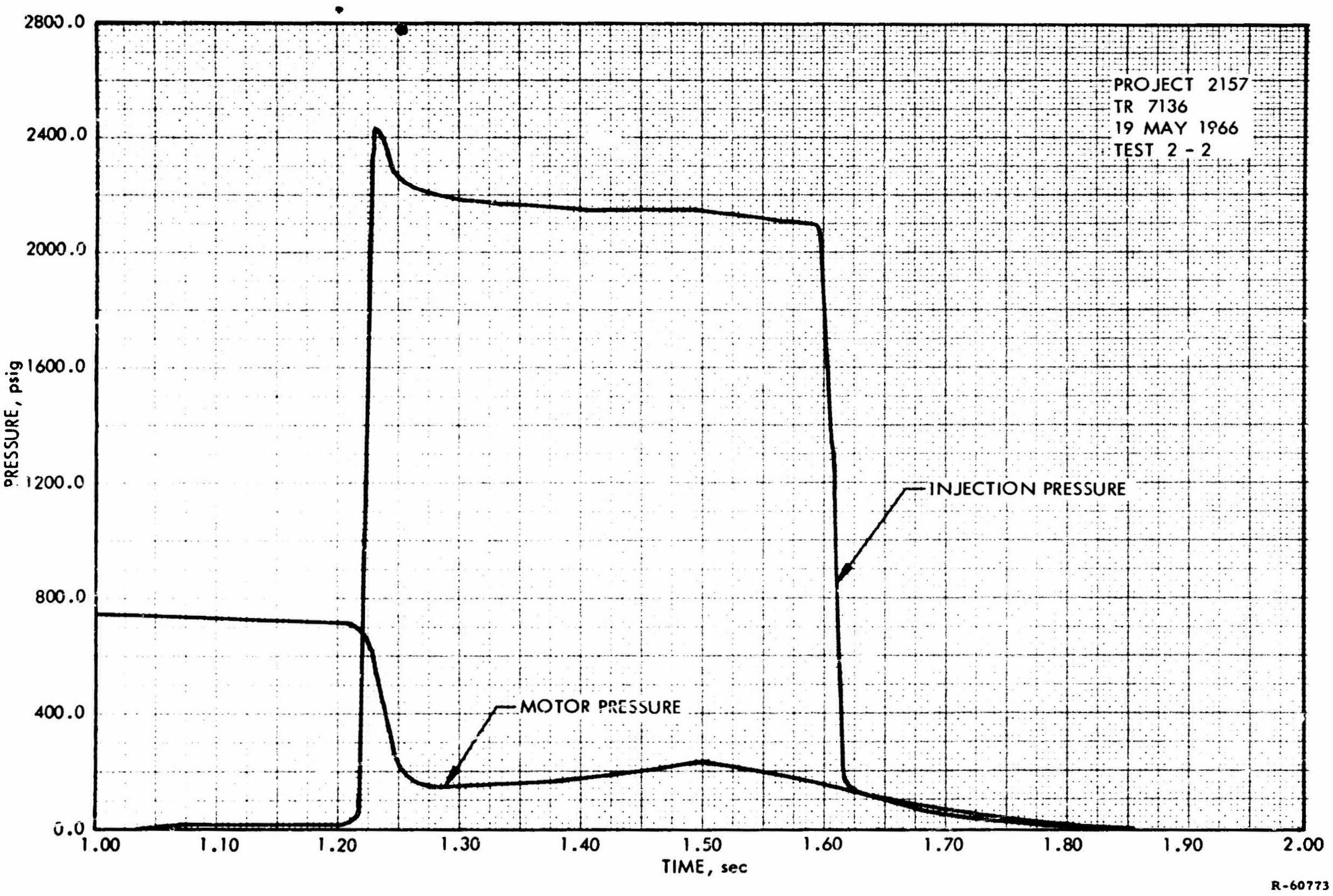


Figure 56. Pressure vs Time Transient, Test 2-2

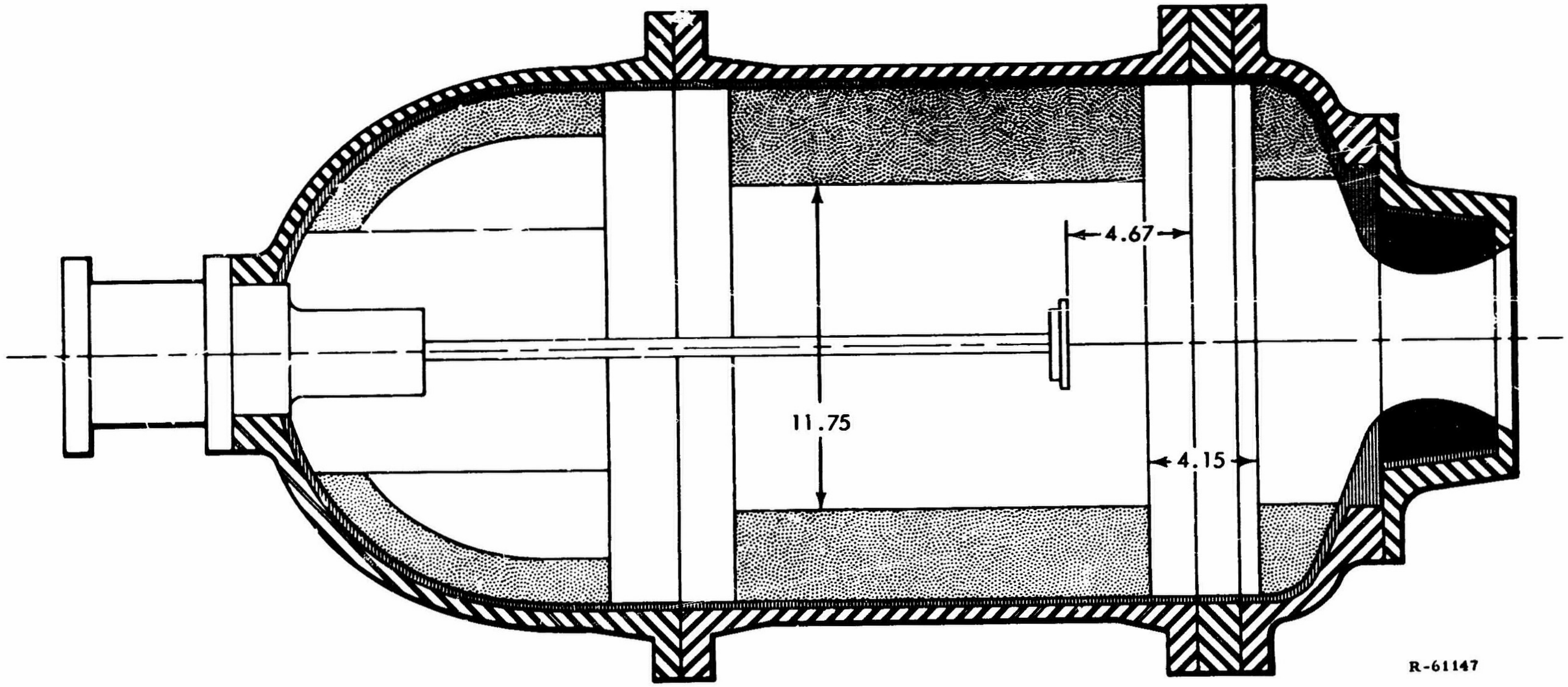


Figure 57. Deflector Position, Relative to the Propellant Surface at the Time of Injection, Test 2-3

the primary system was actuated. Combustion was immediately terminated by the primary system, as evidenced both on the television monitor and by the visual chamber pressure monitor. The pressure versus time transient is shown in figures 58 and 59. The motor was then disassembled for posttest inspection. Visual inspection of the extinguished propellant surfaces revealed evidence of the potholes uncovered after the second firing (see figures 60, 61, 62, and 63). Other irregularities were visible on the propellant surface, but these were not hemispherical in shape as were those from the previous firing. It was also determined that at the low injectant pressure used in this test, the burst diaphragms around the injector failed to open completely. This resulted in a delay between the explosive valve actuation and actual opening of the injector. The actual delay was approximately 400 msec.

Based on the encouraging results of tests conducted in motor No. 2, preparations were made to conduct extinguishment tests in motor No. 3. This motor was identical in configuration to motor No. 2, consisting of a single center segment with a cylindrical port, an aft closure, and a forward closure. One cold-flow and two extinguishment tests were conducted in this motor.

From the two previous tests, it appeared that the slot geometry and the position of the deflector relative to the aft slot had a significant effect on the probability of accomplishing extinguishment. Therefore the cold flow was directed toward further investigation of this idea.

To provide a direct comparison between this cold flow and the cold flow conducted in motor No. 2, the injection pressure was adjusted to provide an injectant flow rate of 300 lb/sec and the piston stroke was adjusted to 21 in., 5 in. shorter than on the motor No. 2 cold flow. The positions of the deflectors in relation to the slot is shown in figure 64.

The cold-flow test was then conducted to establish the actual quantity of water injected into the slot. Spacers were placed at the aft slot to simulate propellant burnback, and a water catcher was located at the slot to sample the quantity of water injected into the slot.

Actuation of the explosively actuated valve resulted in normal injector response. Visual observation of the television monitor and review of the high-speed photos indicated an appreciable amount of water being ejected from the slot. This was verified by the fact that 1.125 lb of water was collected by the catcher. This extrapolates to a total quantity of 21.4 lb, or 18.5% of the total water charge. This is very nearly the same as collected on cold flow No. 2, indicating that the effect of deflector position is either not as important as previously expected or that the deflector position difference was not sufficient to reflect the problem.

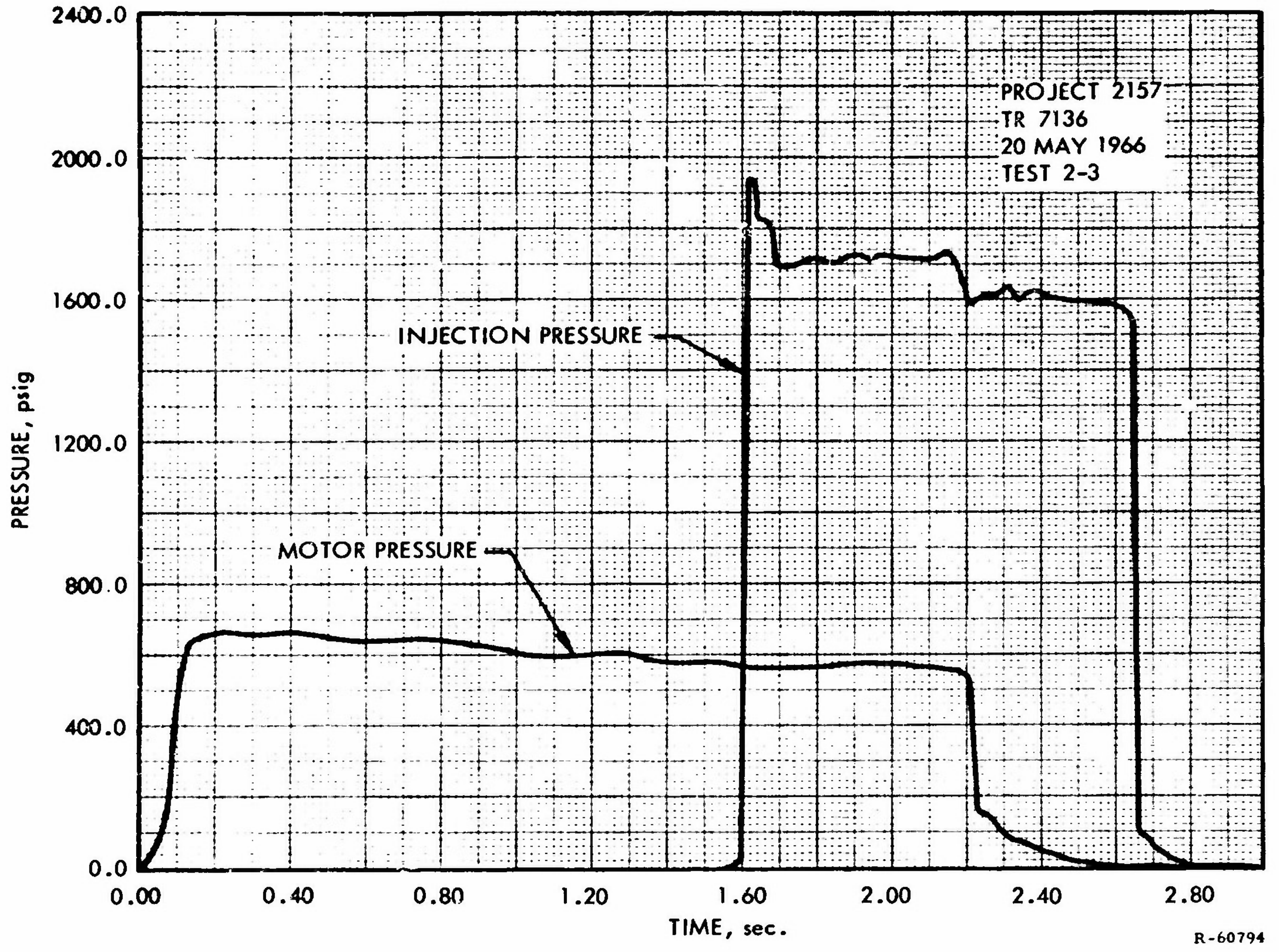
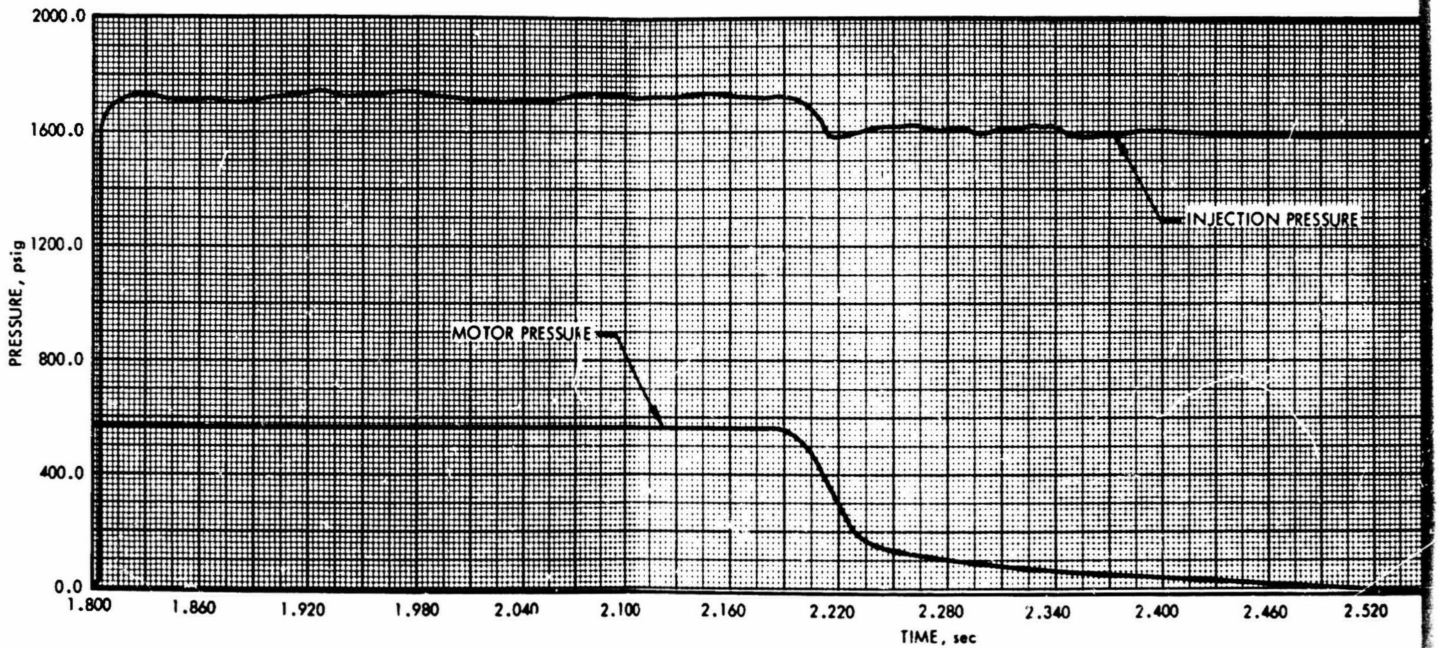


Figure 58. Pressure vs Time Transient, Test 2-3



2000.0
1600.0
1200.0
800.0
400.0
0.0
PRESSURE, psig
INJECTION PRESSURE
MOTOR PRESSURE
1.800
1.860
1.920
1.980
2.040
2.100
2.160
2.220
2.280
2.340
2.400
2.460
2.520
TIME, sec

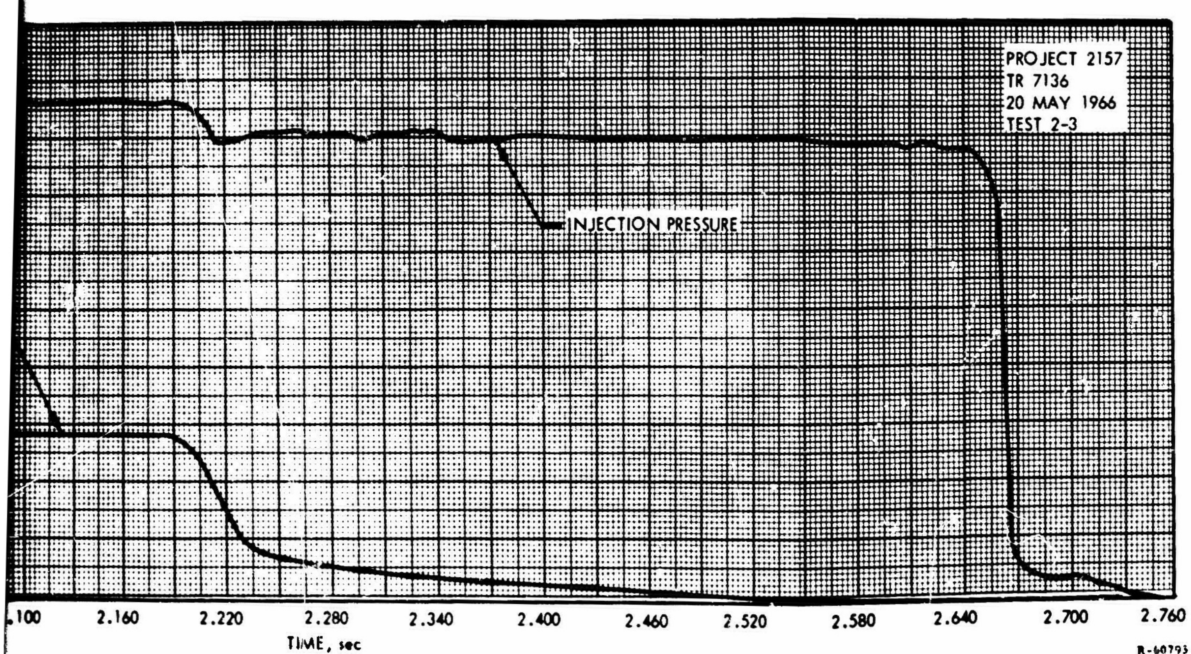


Figure 59. Pressure vs Time Transient, Test 2-3

3

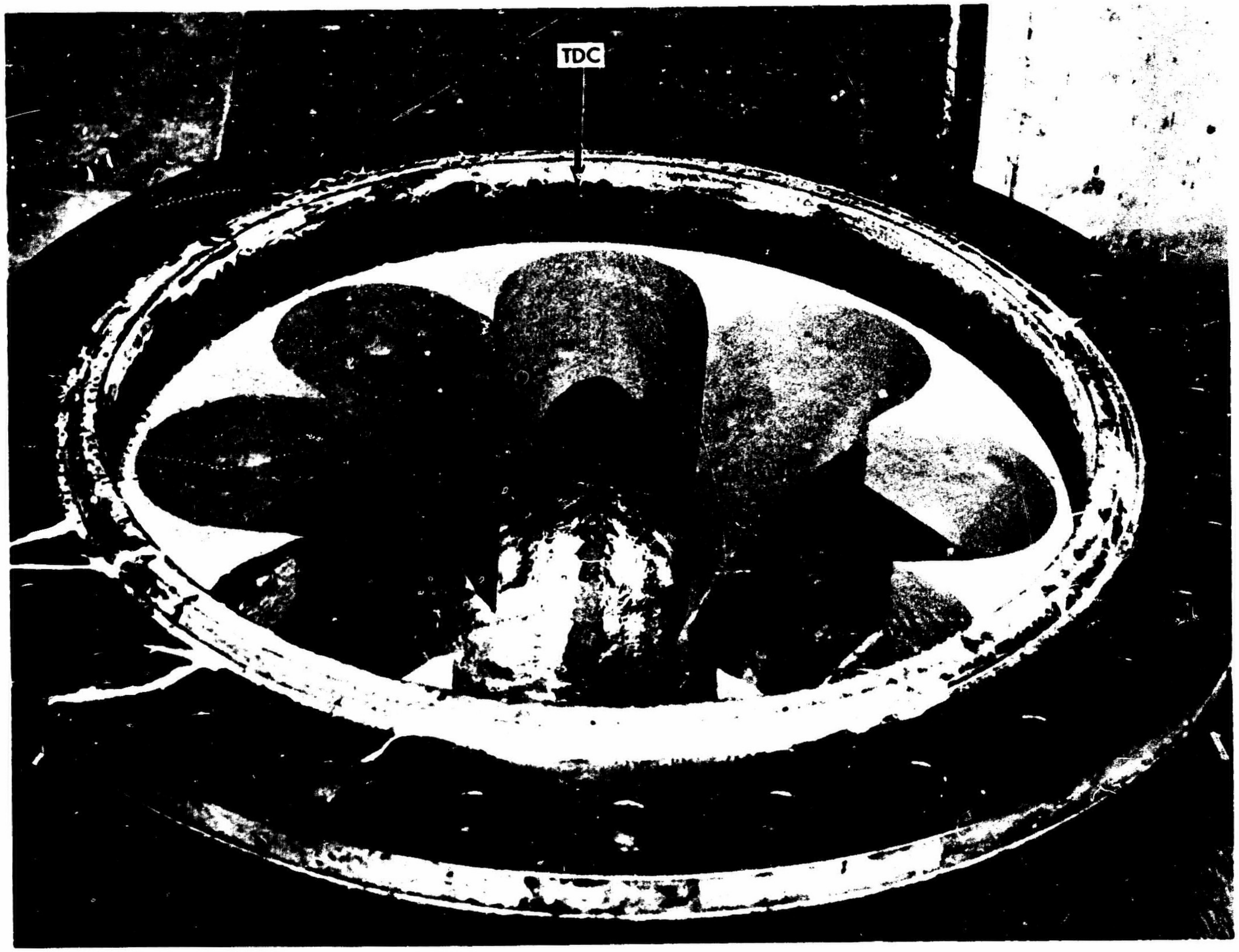


Figure 60. Postfire View of Forward Closure

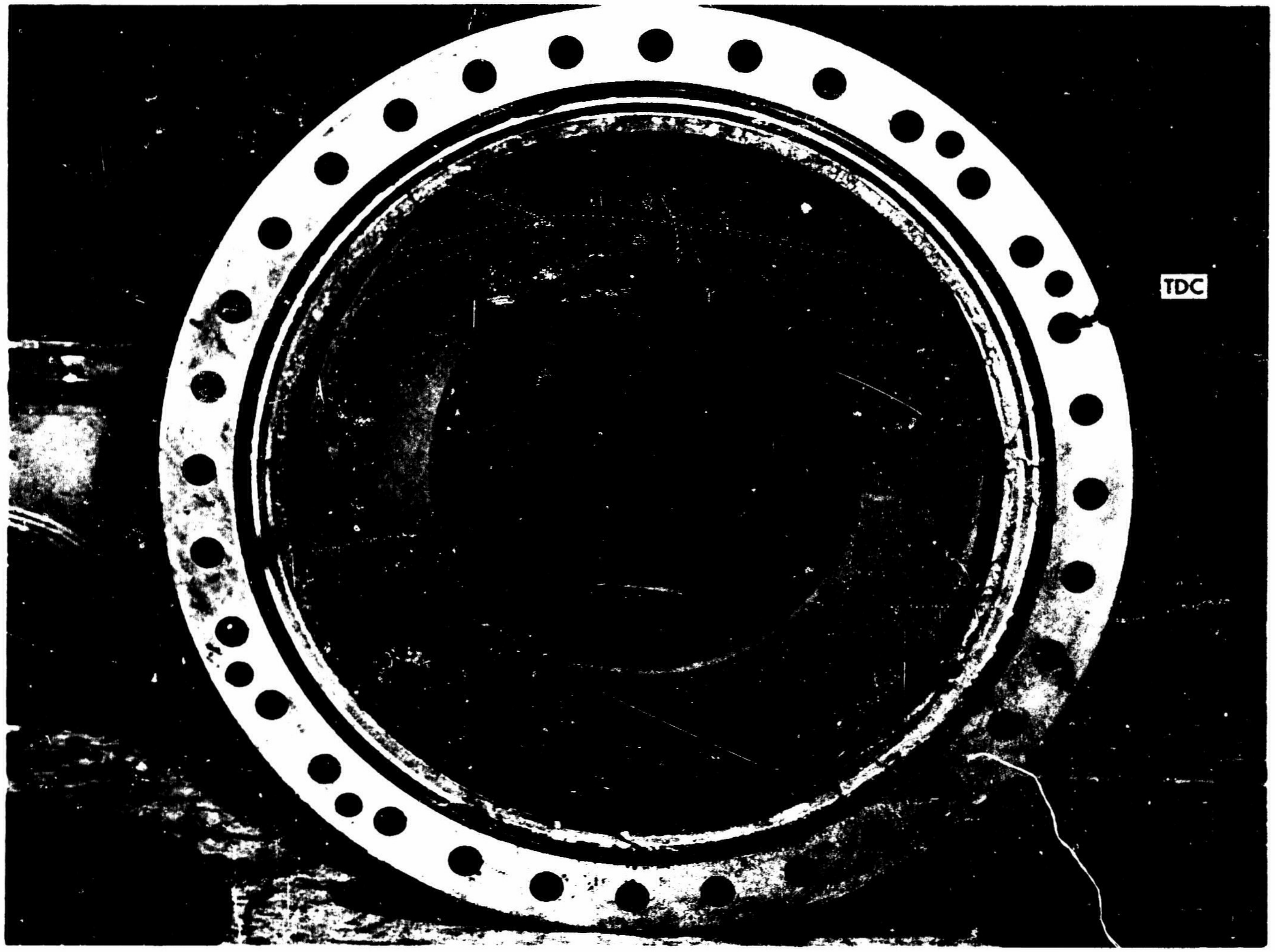


Figure 61. Postfire View of Segment

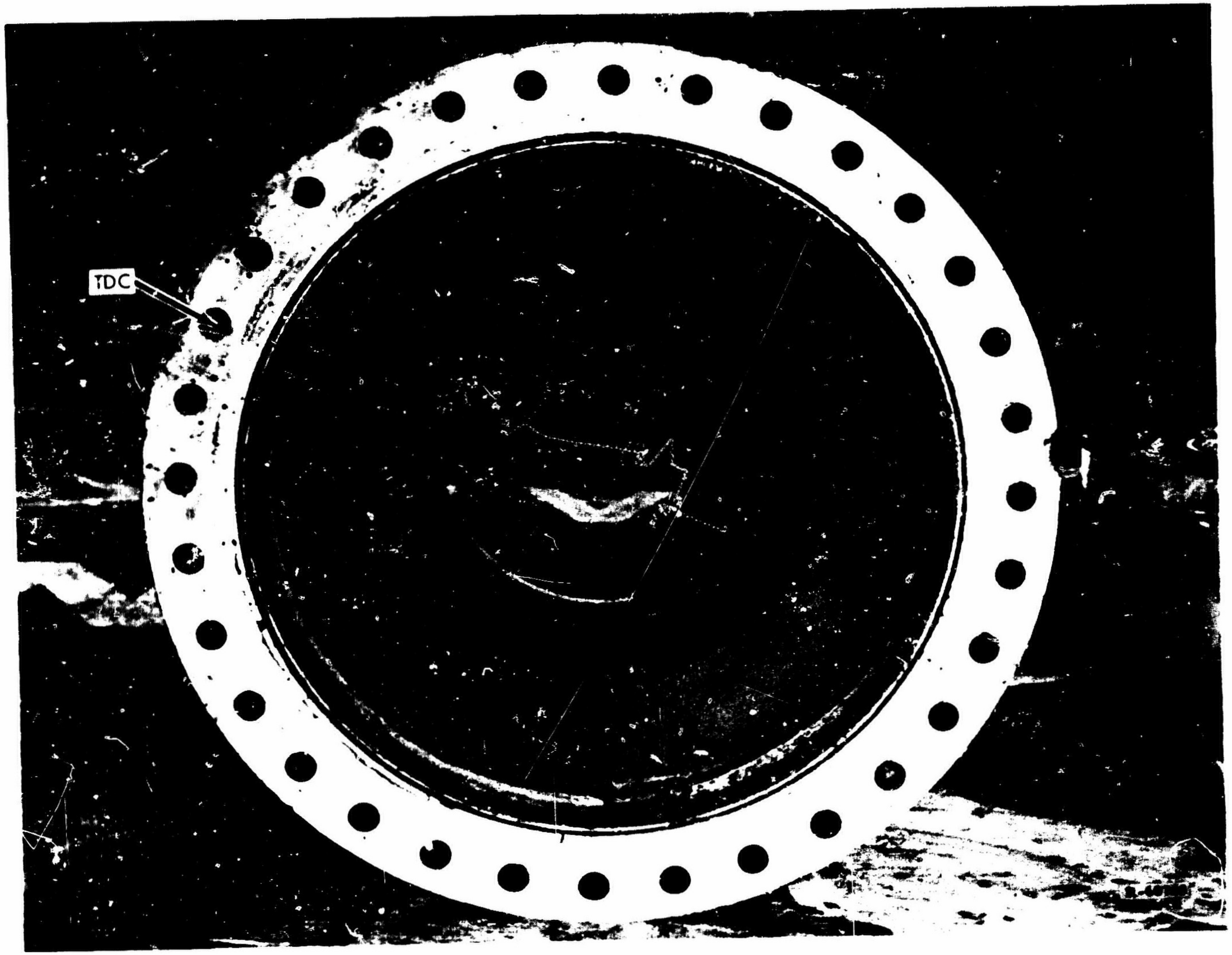


Figure 62. Postfire View of Segment

IDENTIFICATION	CURRENT STATEMENT	AUTHORITY
AD-[illegible] [illegible] CENTER [illegible] Rept. no. UTC-[illegible] Oct 60 Contract AF 04(645)-[illegible]	Approved for public release; distribution unlimited.	[illegible]

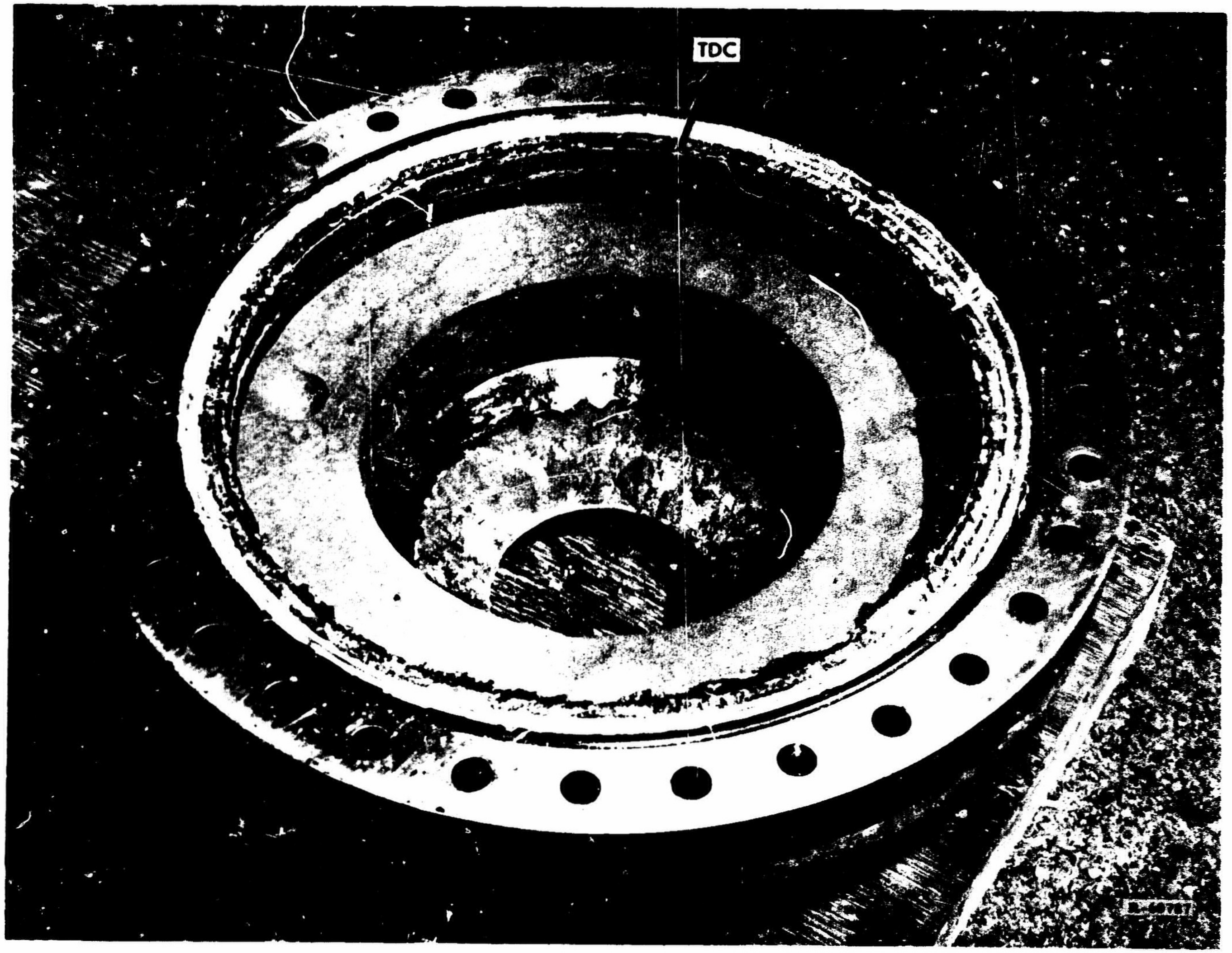


Figure 63. Postfire View of Aft Closure

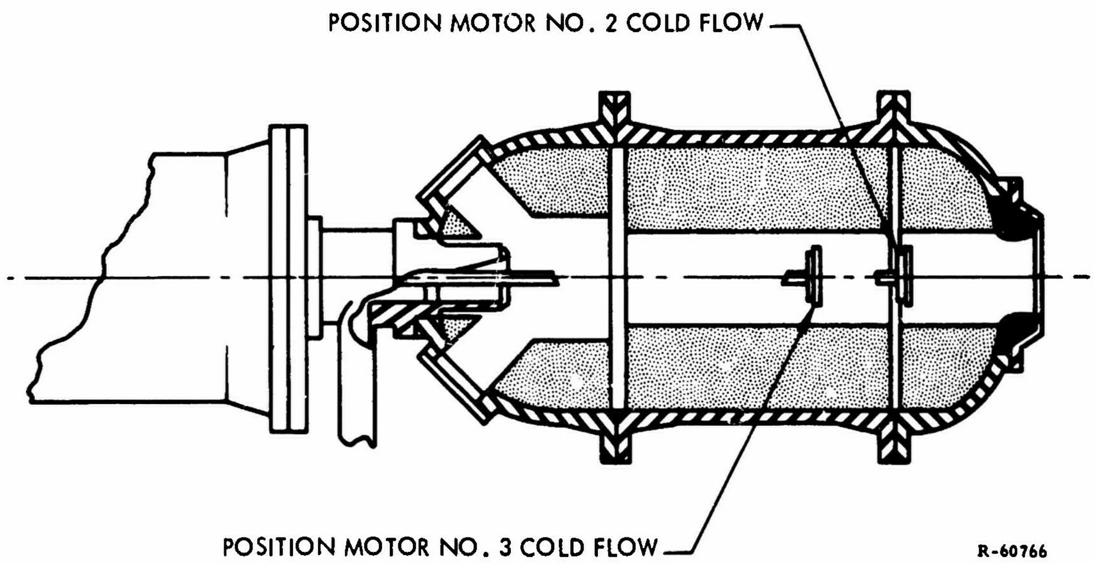


Figure 64. Relative Position of Deflectors
on Cold-Flow Test No. 2 and 3

Preparations were then made for the extinguishment test. All excess water was drained from the motor, and the propellant surfaces were wiped dry and then purged with dry nitrogen.

After both the primary and backup injectors were loaded and the primary system pressurized, the bay was evacuated and the backup system was pressurized. During pressurization of the backup system, it was discovered that the backup actuator valve was not holding pressure. The test was scrubbed and the valve was removed for repair. Examination of the valve revealed that the valve seat was damaged. It was assumed that it had been damaged during the cold-flow test as a result of a downstream pressure shock from the primary system. The valve was repaired, and the plastic (teflon) seat was replaced by a soft copper seat.

The system was reassembled, and both the primary and backup systems were loaded with water and pressurized. The valve was operated several times and appeared to both operate normally and hold pressure.

The first extinguishment test was then conducted using the same injection parameters used in the cold-flow (see design point 3-1 on figure 40). The deflector position relative to the propellant surfaces at the time of injection is shown in figure 65. The motor was ignited and allowed to burn for 2 sec before the

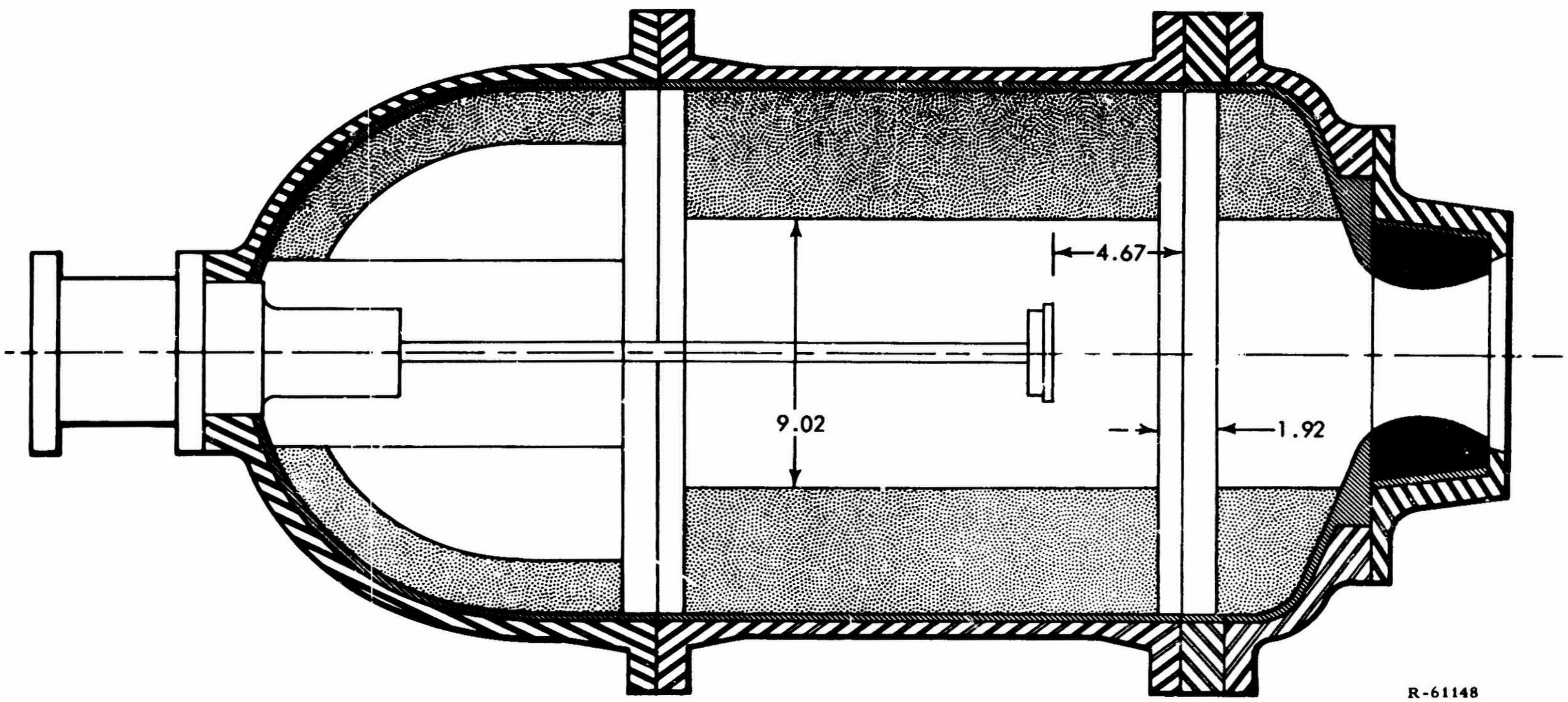


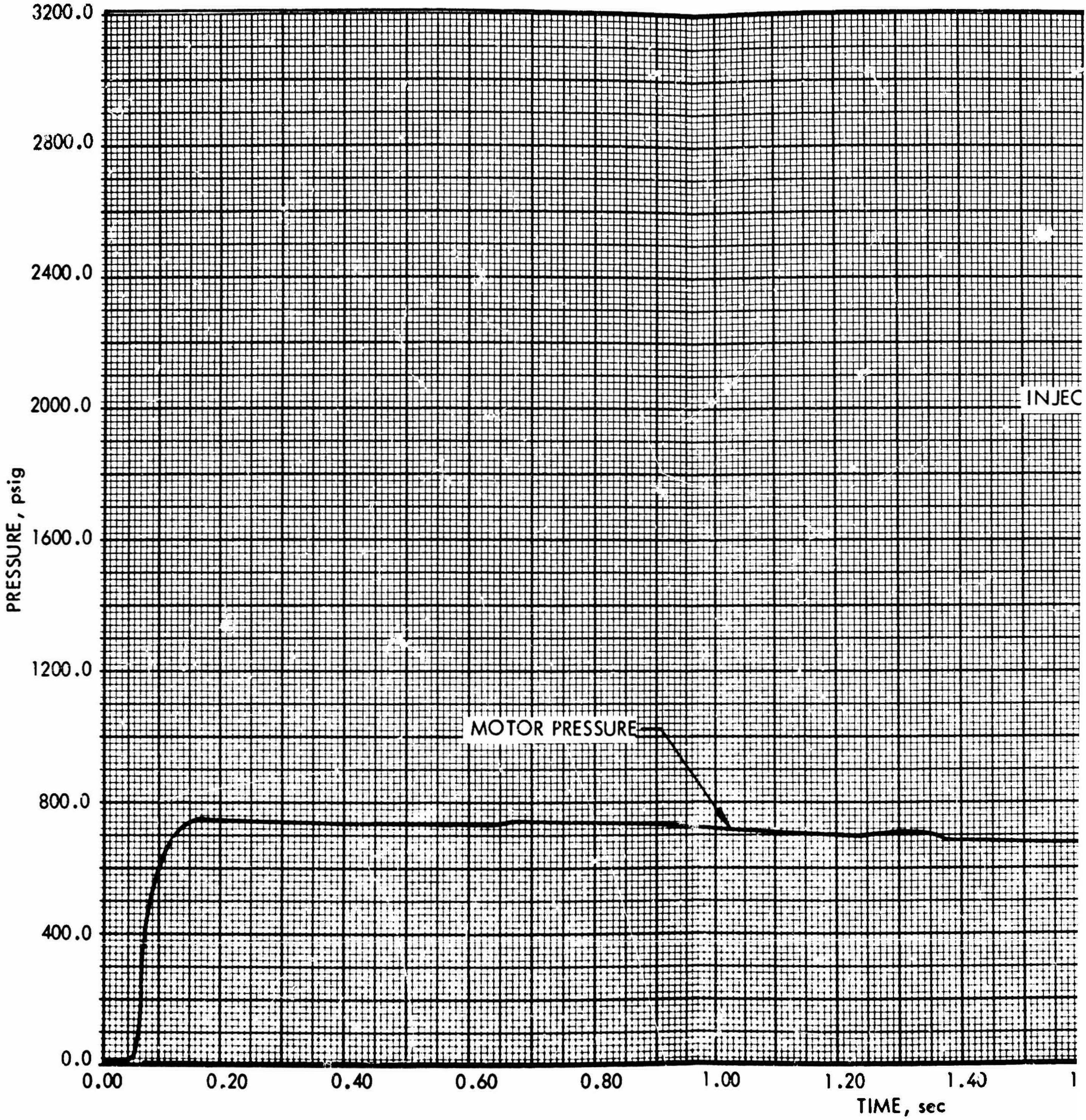
Figure 65. Deflector Position, Relative to the Propellant Surface at the Time of Injection, Test 3-1

primary injector was actuated. Visual observation of the test on the television monitor revealed that the motor was extinguished immediately, and posttest examination of the motor revealed uniform burning over the entire propellant surface. Posttest dimensional inspection of the motor revealed that a 3.84-in.-diameter nozzle throat had inadvertently been used in place of the 3.39-in.-diameter throat. This resulted in a lower than expected chamber pressure and flow rate; however, the change was not sufficient to cause any appreciable changes in the important parameter of propellant mass flow rate, i.e., 46.5 lb/sec instead of 50 lb/sec. The pressure versus time transient of the test is shown in figures 66 and 67.

In an effort to further investigate the effect of the deflector position on motor extinguishment, the control rod was shortened to 16 in. and the flow rate was adjusted to provide a design point near those of the previous three tests (see design point 3-2, figure 40). The deflector position relative to the propellant surfaces at the time of injection is shown in figure 68.

The motor was ignited and allowed to burn for 1.0 sec before the primary system was actuated. Steam and water were in evidence at the motor throat, but it was immediately obvious that the motor was not going to terminate. The backup system was then actuated, but this system also failed to provide extinguishment and the motor burned to completion. Posttest examination of the system revealed that the backup actuator valve had failed to open completely, and although the entire backup charge of 500 lb of water had been injected through the motor, it had been injected at a reduced flow rate of approximately 48 lb/sec. Disassembly of the valve revealed that pressure had leaked behind the copper seat and had collapsed the seat against the valve orifice, thereby restricting water flow. The pressure versus time transient shown in figures 69 and 70 clearly shows the various events in the test. Posttest examination of the disassembled motor provided substantial proof that the aft slot area had never been extinguished during the test. The charred surface of the segment insulator, figure 71, shows that propellant burnout occurred in the lower portion of the segment near the forward end. As normal surface regression would have resulted in burnout of the propellant in a uniform band at the center of the segment, it can be assumed that although the forward end of the segment was extinguished the aft end continued burning.

This completed the testing of the single-segment TM-3A test motors. As a result of these tests, two major conclusions were drawn: (1) the aft slot was established as the most difficult area of the motor to extinguish, and (2) in order to provide adequate flow into the slot with this grain design, it was necessary to extend the deflector to a position adjacent to the aft slot. On this basis, it was considered unreasonable to conduct further tests in a grain configuration which required a mechanical deflector to direct water


3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
PRESSURE, psig
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
TIME, sec
MOTOR PRESSURE
INJEC

A

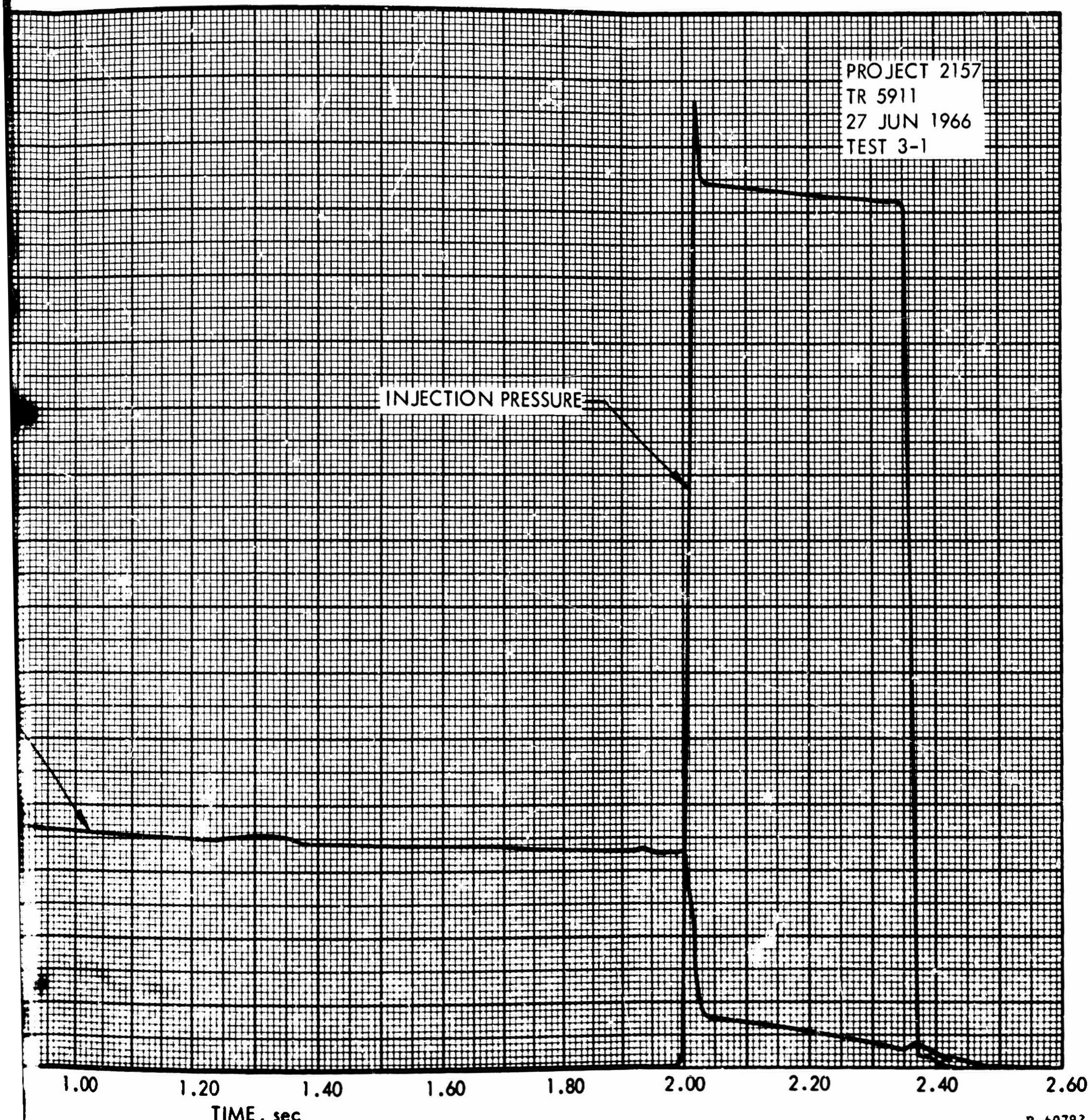
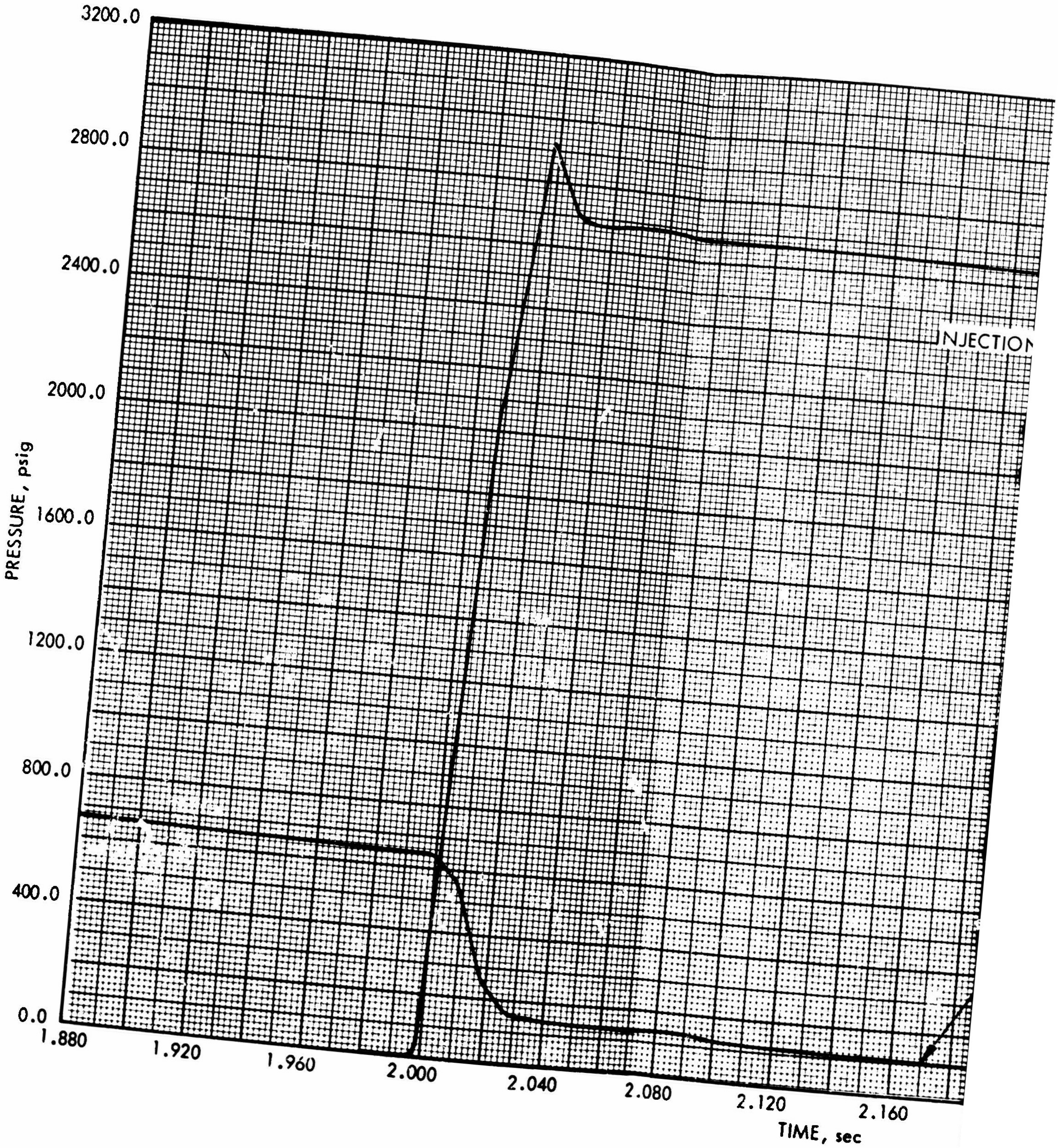


Figure 66. Pressure vs Time Transient, Test 3-1

B



3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
PRESSURE, psig
INJECTION
1.880
1.920
1.960
2.000
2.040
2.080
2.120
2.160
TIME, sec

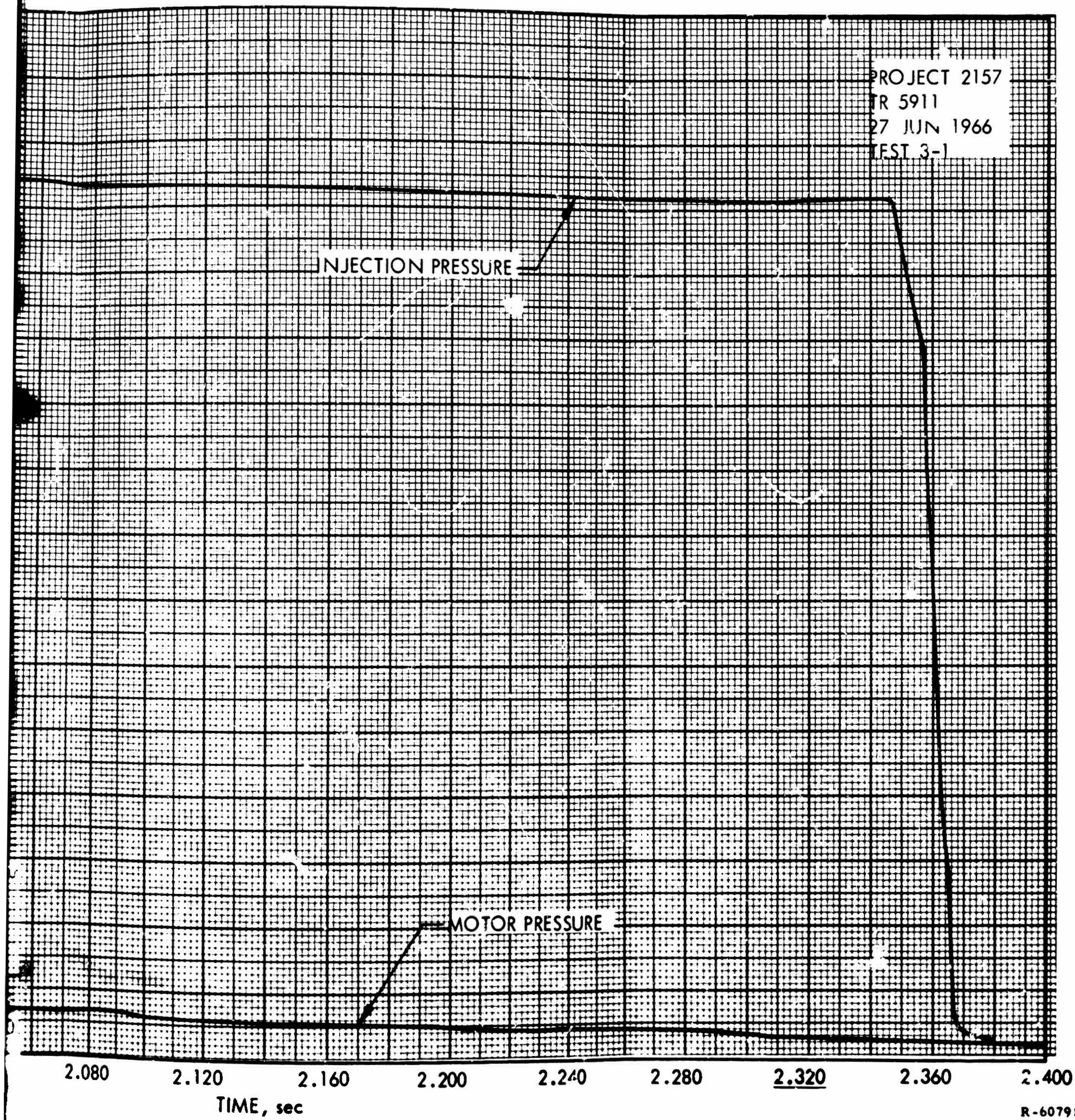


Figure 67. Pressure vs Time Transient, Test 3-1

13

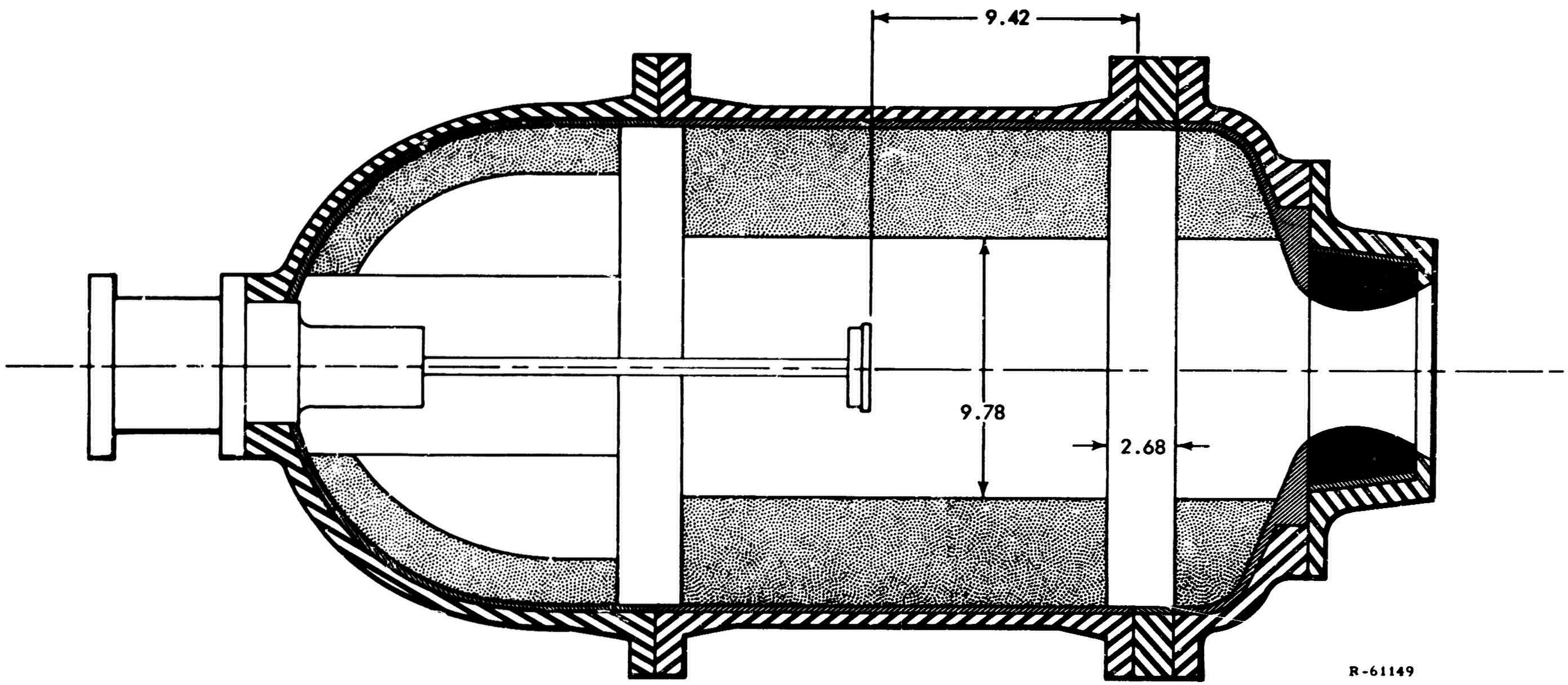
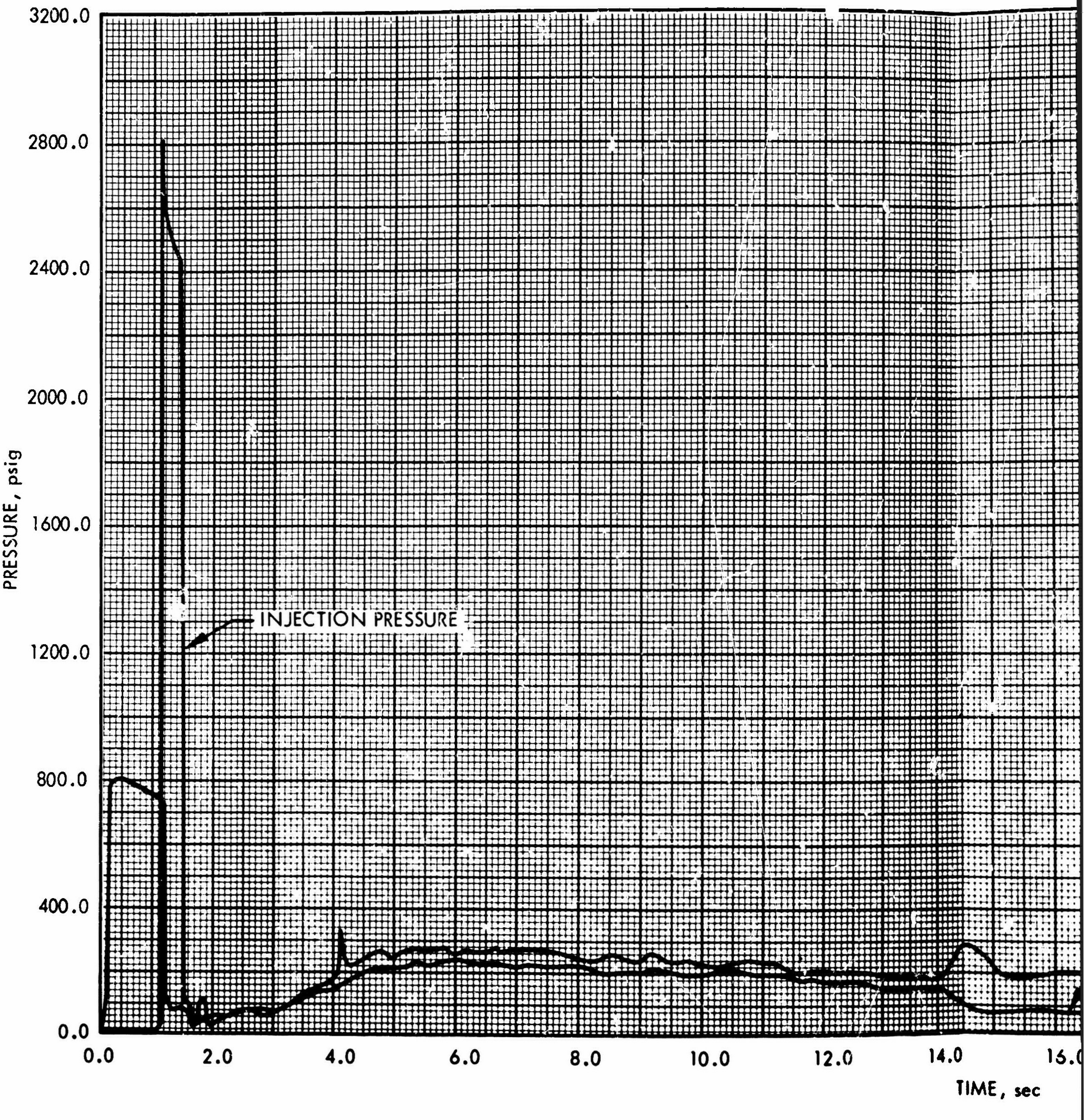


Figure 68. Deflector Position, Relative to the Propellant Surfaces at the Time of Injection, Test 3-2


3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
PRESSURE, psig
INJECTION PRESSURE
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
TIME, sec

A

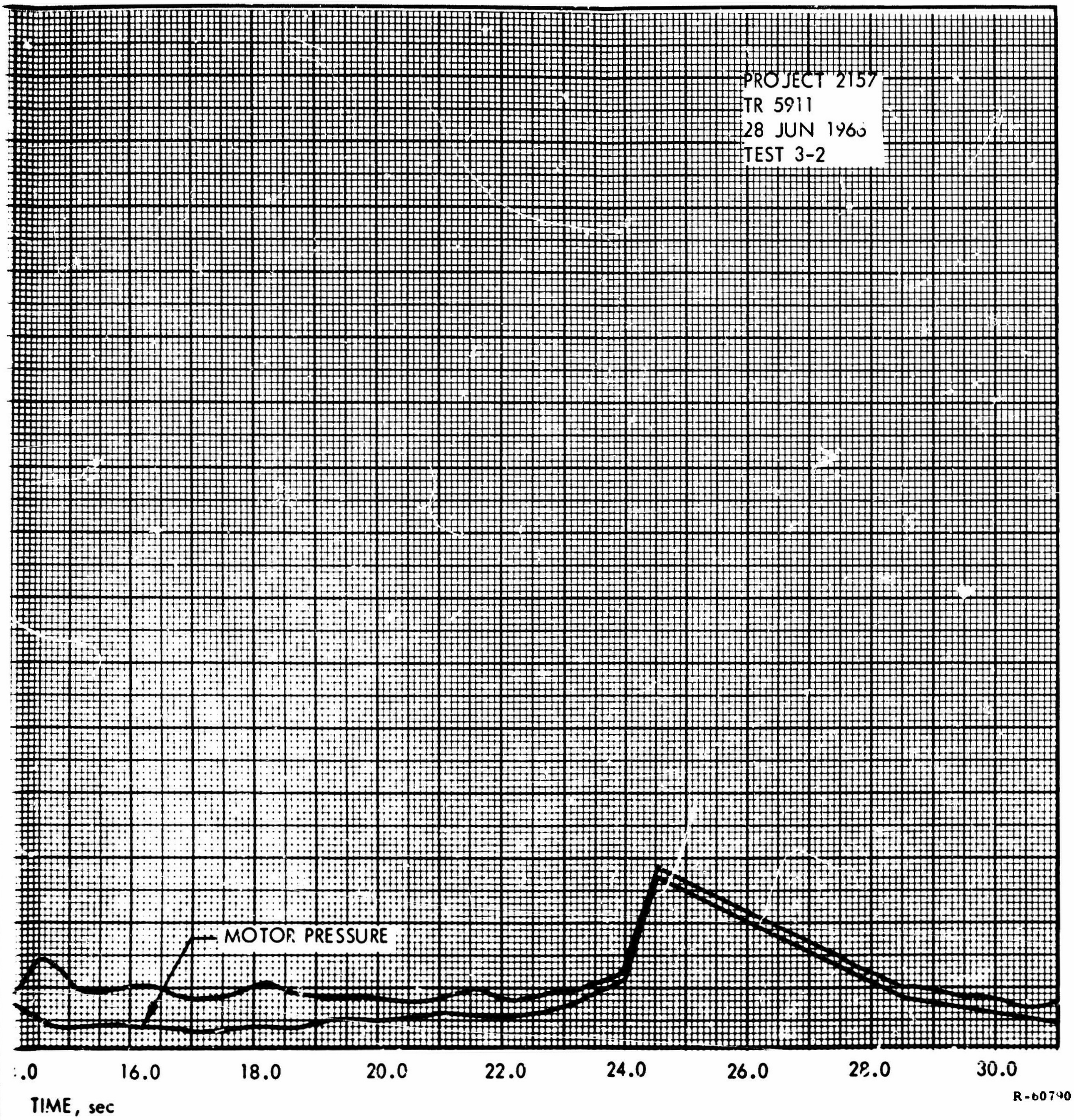
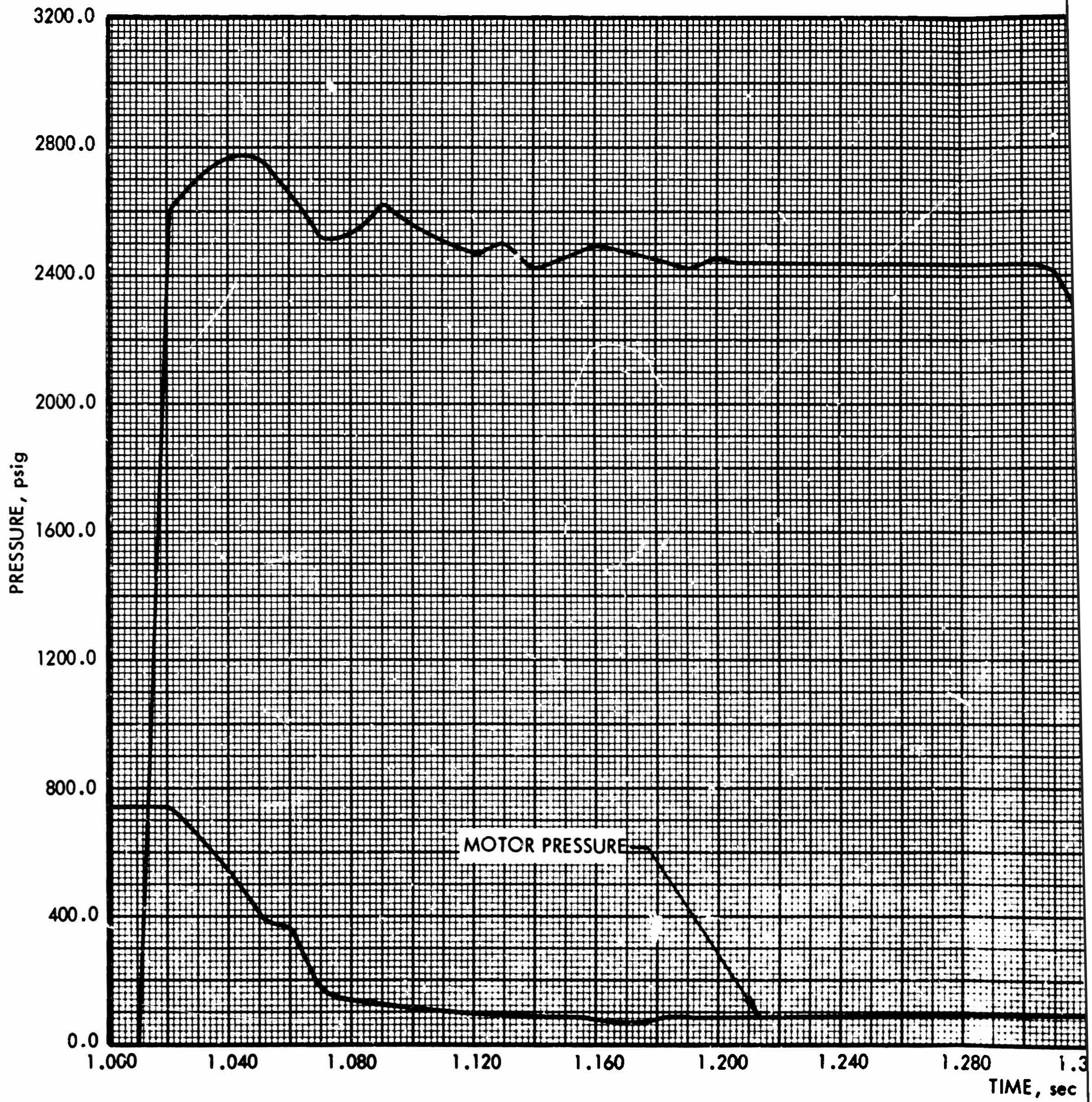


Figure 69. Pressure vs Time Transient, Test 3-2

B


3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
PRESSURE, psig
MOTOR PRESSURE
1.000
1.040
1.080
1.120
1.160
1.200
1.240
1.280
TIME, sec

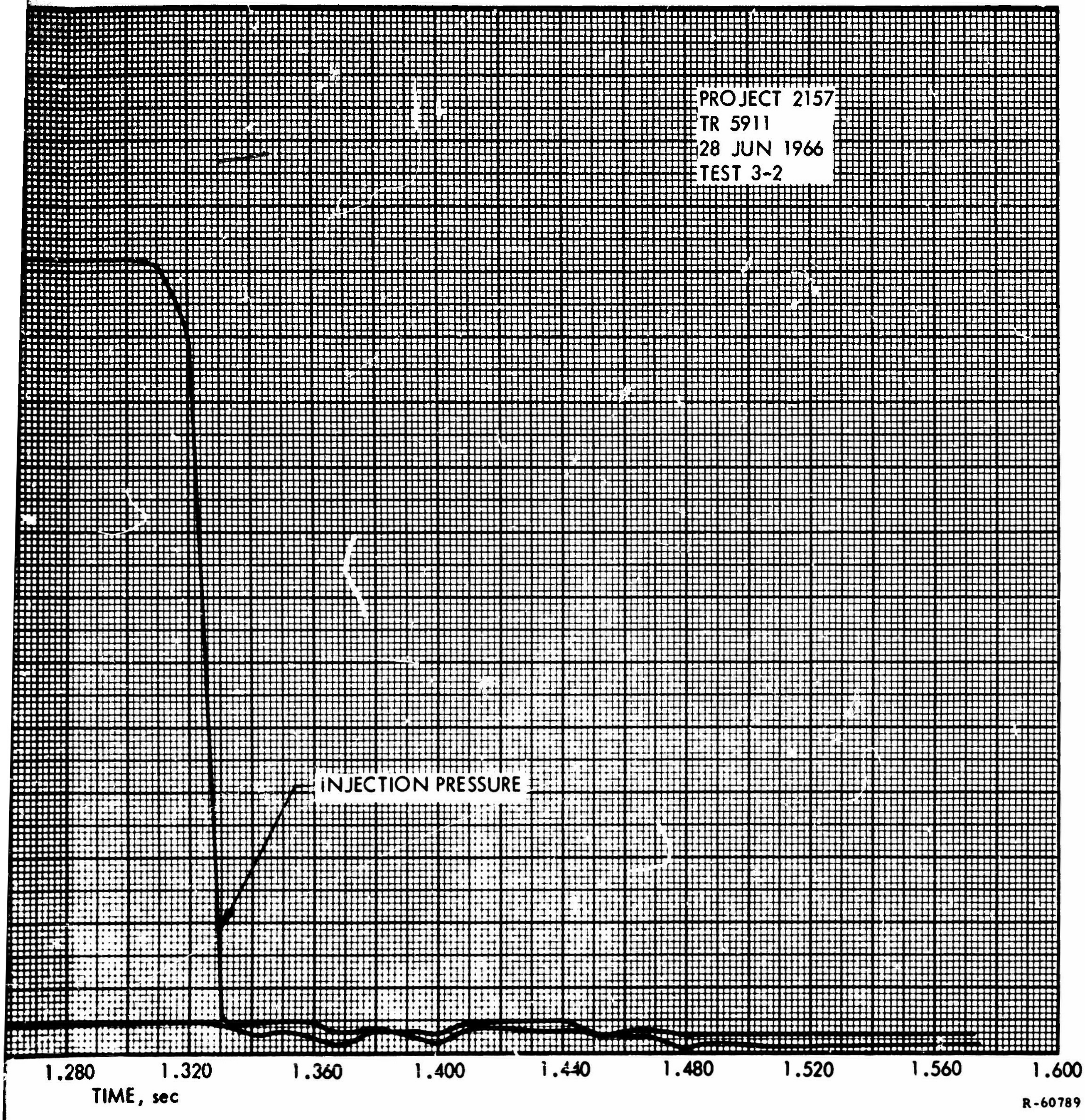


Figure 70. Pressure vs Time Transient, Test 3-2

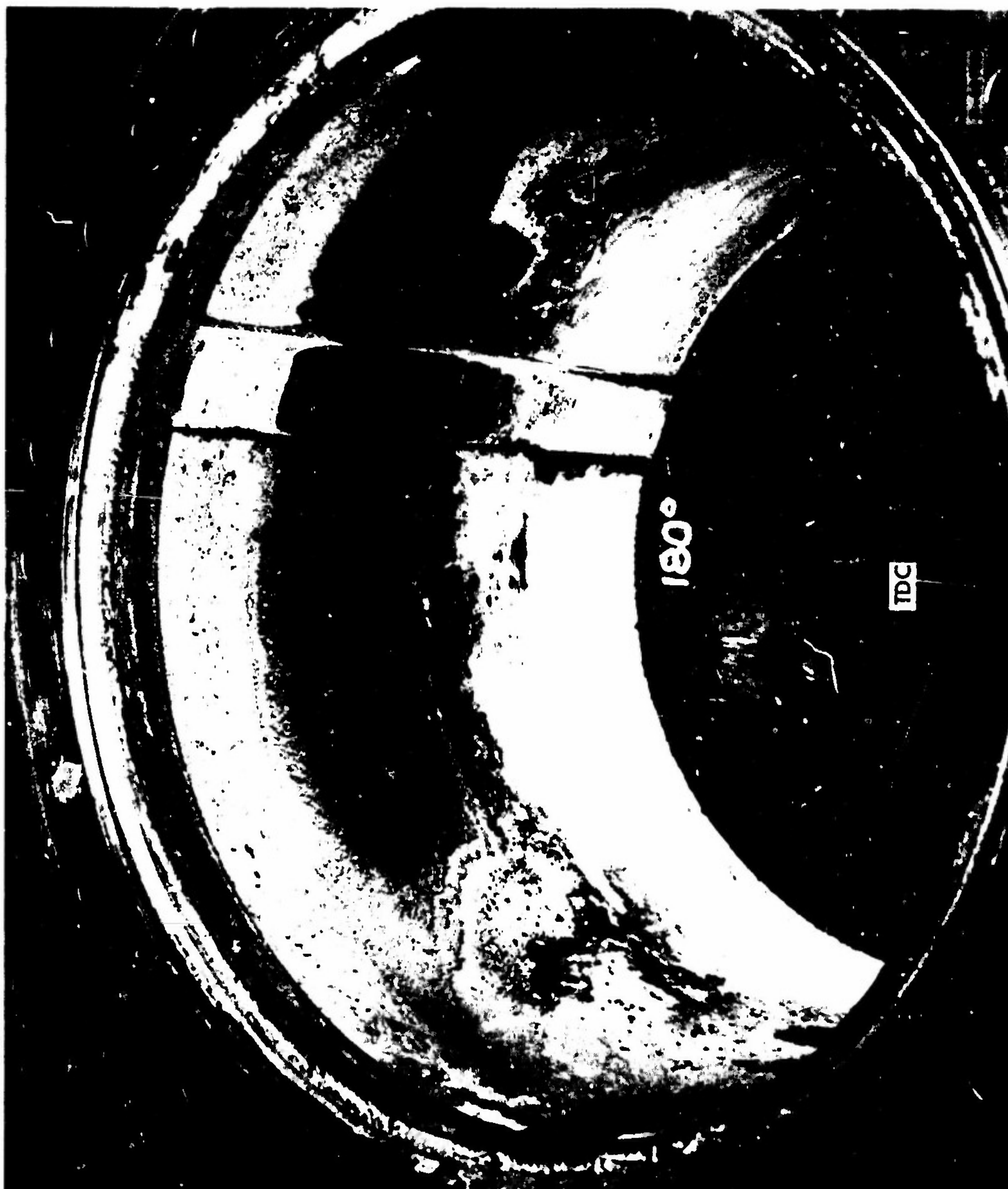


Figure 71. Postfire View of the Segment, Test 3-2

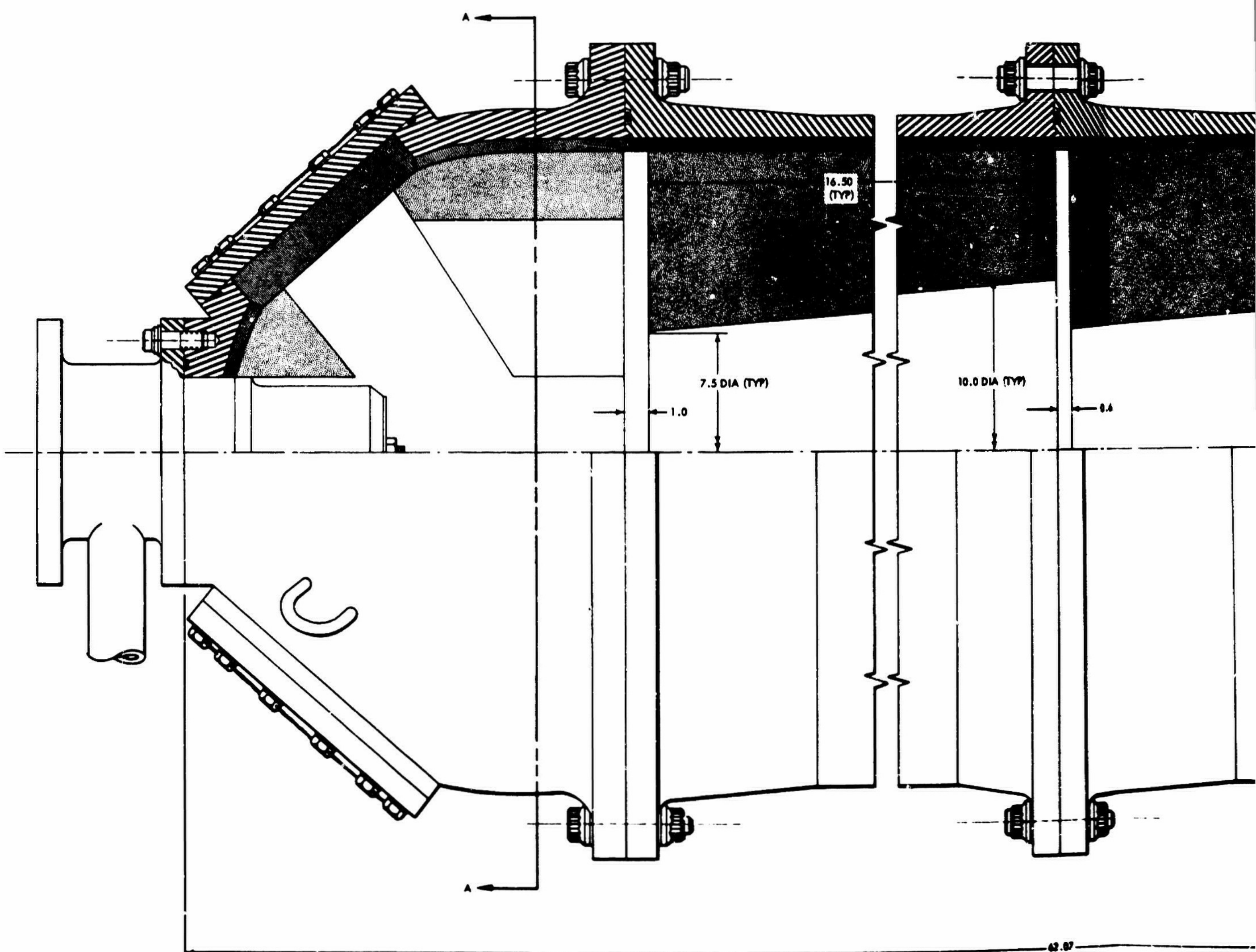
into the slot areas. For this reason, the grain configuration for the two-segment motors was modified to provide a slot configuration which would be easier to extinguish. The grain design selected is shown in figure 72. This design is similar to the Titan III-C booster except that the diameter of the segment at the aft slot is smaller than the diameter of the port in the aft closure and the forward surface of the segment is unrestricted. The predicted pressure for this grain design is shown in figure 73. With this design, it was speculated that water moving at high velocities down the port would impinge on the downstream propellant surface and disperse into the slot. The amount of water deflected into the slot would be dependent on the diameter differences between adjacent slot surfaces. In this manner, the water requirement could be established and the grain design adjusted accordingly.

The segment grain design selected for the remaining two motors utilized an internal-burning tapered tube 7-1/2 in. in diameter at the forward end and 10 in. in diameter at the aft end. Assuming a uniform injectant flow density and a 50% efficiency factor, this slot configuration should capture approximately 20% of the total water injected. Considering that the slot constitutes less than 15% of the total surface area, this design should provide adequate water dispersion into the slot to provide extinguishment.

Two TM-3A two-segment motors were then processed to this configuration. One motor was assembled and mounted in the test bay for cold-flow testing. As in earlier cold-flow tests, spacers were placed between the aft segment and aft closure to simulate the propellant surface burnback, and a catcher was located at the opening to sample the water injected through the slot.

The control rod of the primary injector was adjusted to provide a stroke of 38.6 in. This resulted in a water charge of 214 lb. The GN_2 pressurization system was pressurized to 2,160 psi to simulate the ΔP predicted in an actual motor extinguishment test. At this charge weight and flow rate, the injector is providing the maximum design output.

The cold-flow test was then conducted; the injector operated normally. Visual observation of the test on the television monitor indicated an abundance of water ejected from the aft slot. Posttest inspection of the catcher verified this observation (4.06 lb of water was collected by the catcher). Considering that the catcher covered only 4.0 in. of the 76.4-in. motor circumference, it can be determined by extrapolation that 77.5 lb, or 36.4%, of the water was deflected into the slot.


A
16.50
(TYP)
7.5 DIA (TYP)
1.0
10.0 DIA (TYP)
A

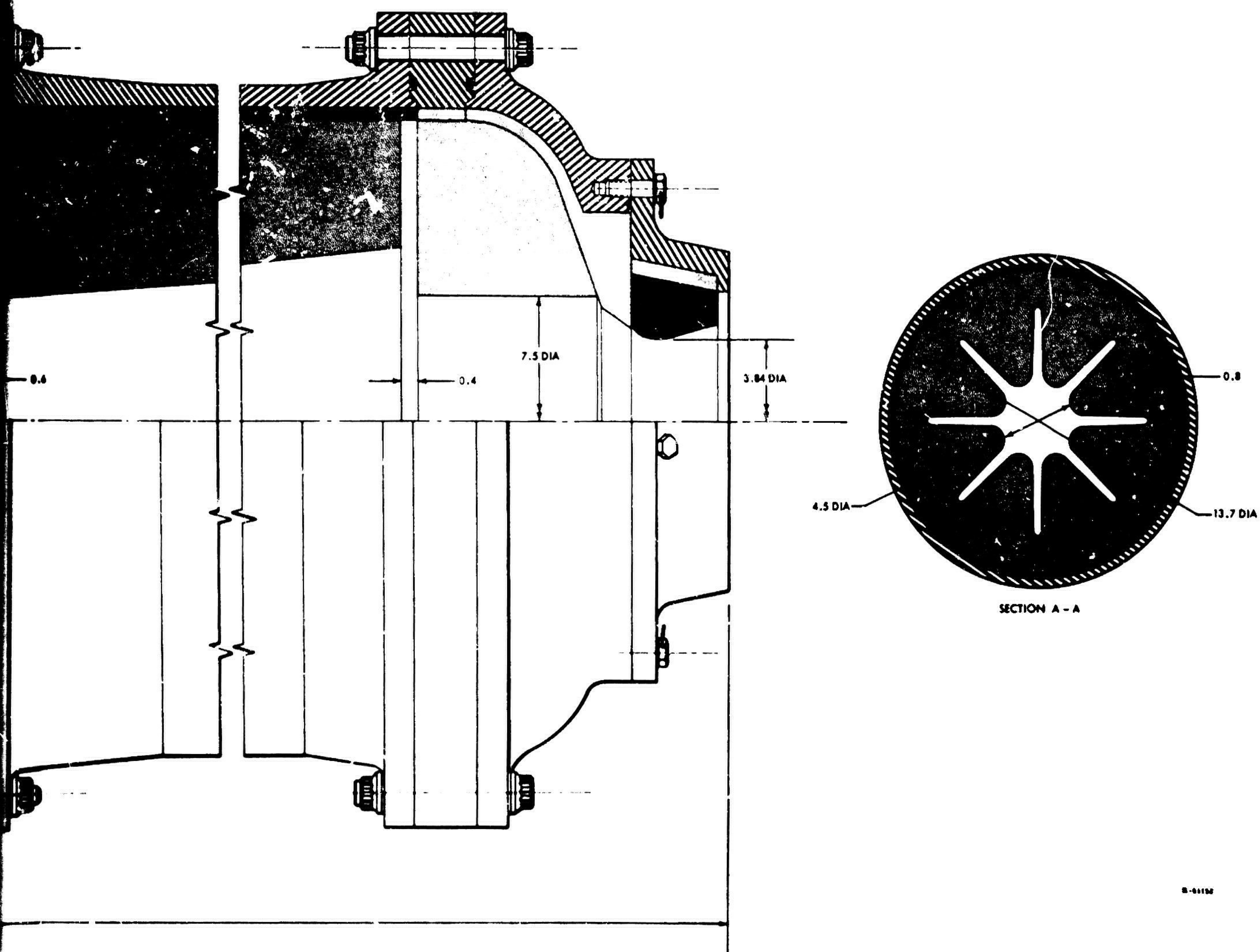


Figure 72. Two-Segment TM-3A Motor Configuration

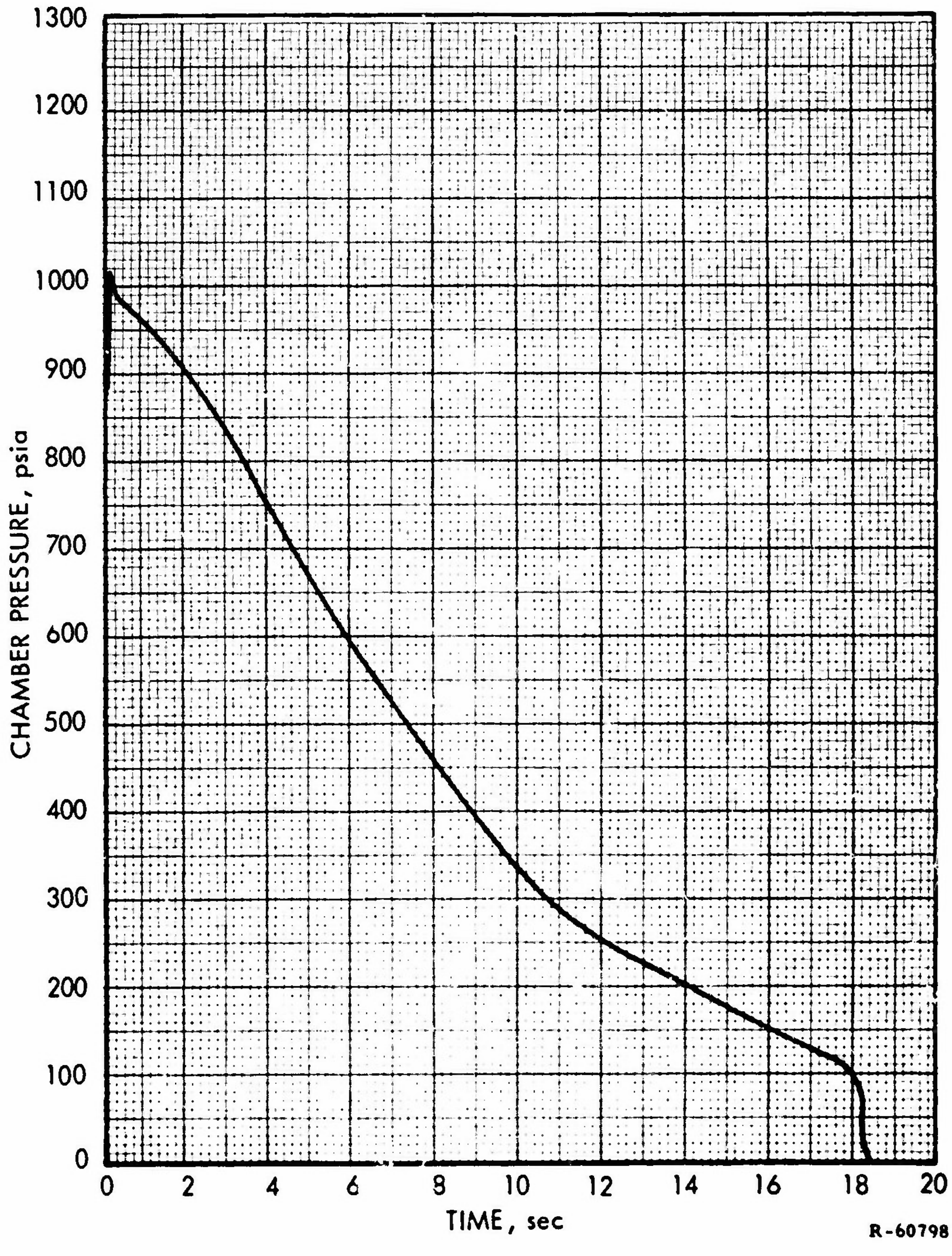


Figure 73. Two Segment TM-3A Pressure vs Time Transient

The results of this test are higher than predicted because in this test the deflector moved sufficiently close to the slot to have an effect on the water distribution.

All excess water was drained from the motor, and the propellant surface was wiped dry and then purged with dry nitrogen. The injector was refurbished and charged with water.

All injection parameters (piston travel, injectant quantity, and flow rate) were set to be the maximum capability of the system. The resulting design point is shown as 4-1 on figure 40.

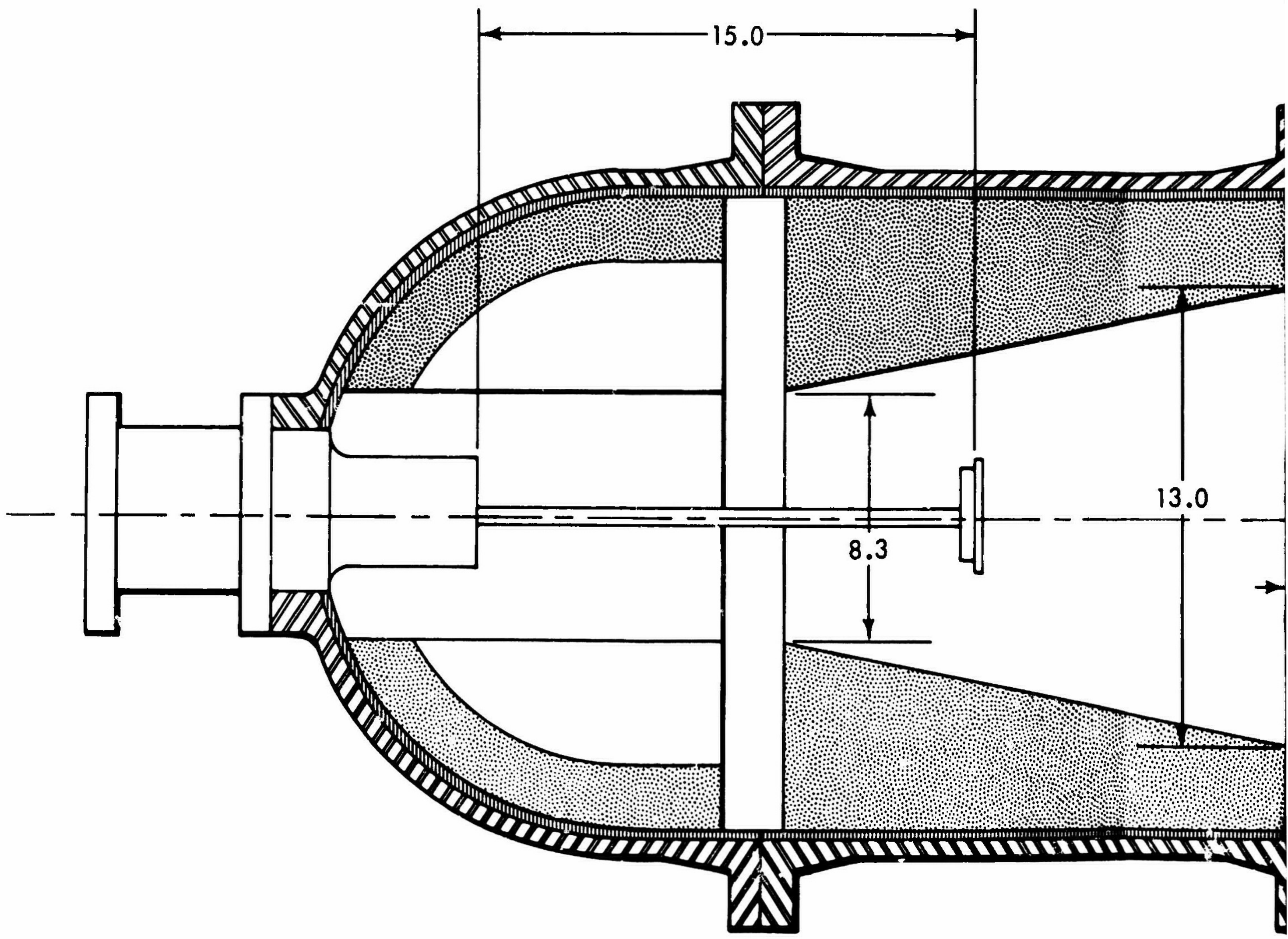
The motor was ignited and allowed to burn for 2 sec before the primary system was actuated. Visual observation of the test on the television monitor revealed immediately that the motor would not be extinguished by the primary system and the backup system was actuated. The backup system was no more effective than the primary system, and the motor burned to completion. Posttest examination of the primary system revealed that after approximately 15 in. of piston travel, the portion of the control rod upstream of the swirl plate collapsed ahead of the piston. Figure 74 shows the final position of the deflector relative to the propellant surfaces at the time of injection. Although the failure affected the final position of the deflector, it had no apparent effect on the movement of the piston or the water flow rate. In addition, at the completion of the test the extended portion of the rod was rigidly retained in the swirl plate housing, and the deflector was located near the center line of the motor.

The backflow of combustion products into the backup plumbing, after the water in the backup system had been expelled, caused considerable damage to the swirl plate and deflector.

Detailed examination of the hardware indicated that the control rod had become bound in the swirl plate and the rod then failed in compression. Binding of the rod in the swirl plate was probably initiated by a whipping action in the rod causing the swirl plate to cock and bind against the threaded portion of the rod.

Posttest examination of the fired motor revealed that propellant burnout had occurred in the forward end of the first segment near the final position of the deflector (see figure 75).

The area of burnout indicated that combustion had progressed from the aft end of the motor forward, consuming the aft segment first and then terminating in the forward end of the forward segment. This is similar to the manner in which the third motor burned and indicates a strong probability of reignition in the aft slot.



A

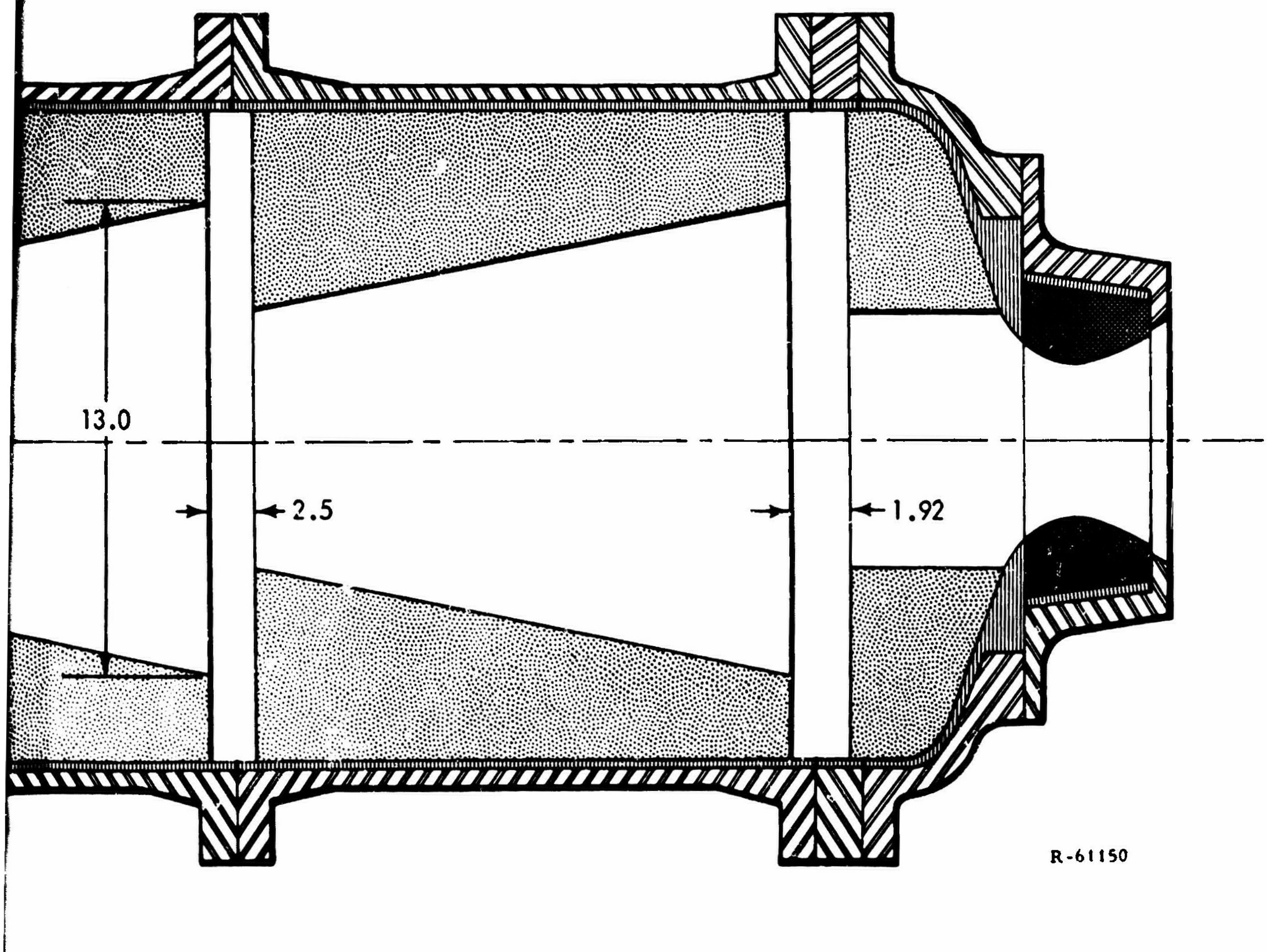


Figure 74. Deflector Position, Relative to the Propellant Surfaces at the Time of Injection, Test 4-1

B

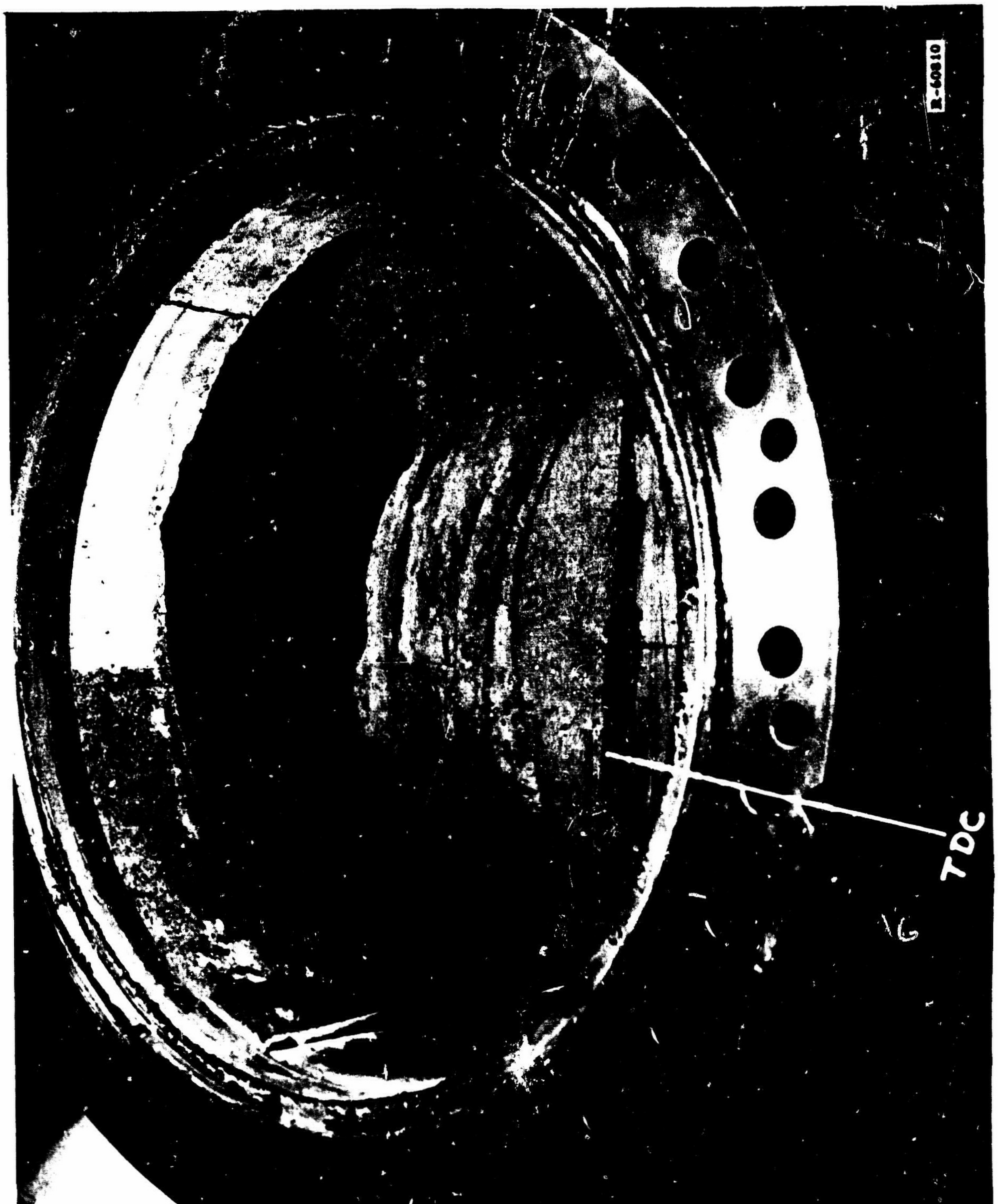


Figure 75. Postfire View of the Segment, Test 4-1

The pressure versus time transient of the test is shown in figures 76 and 77.

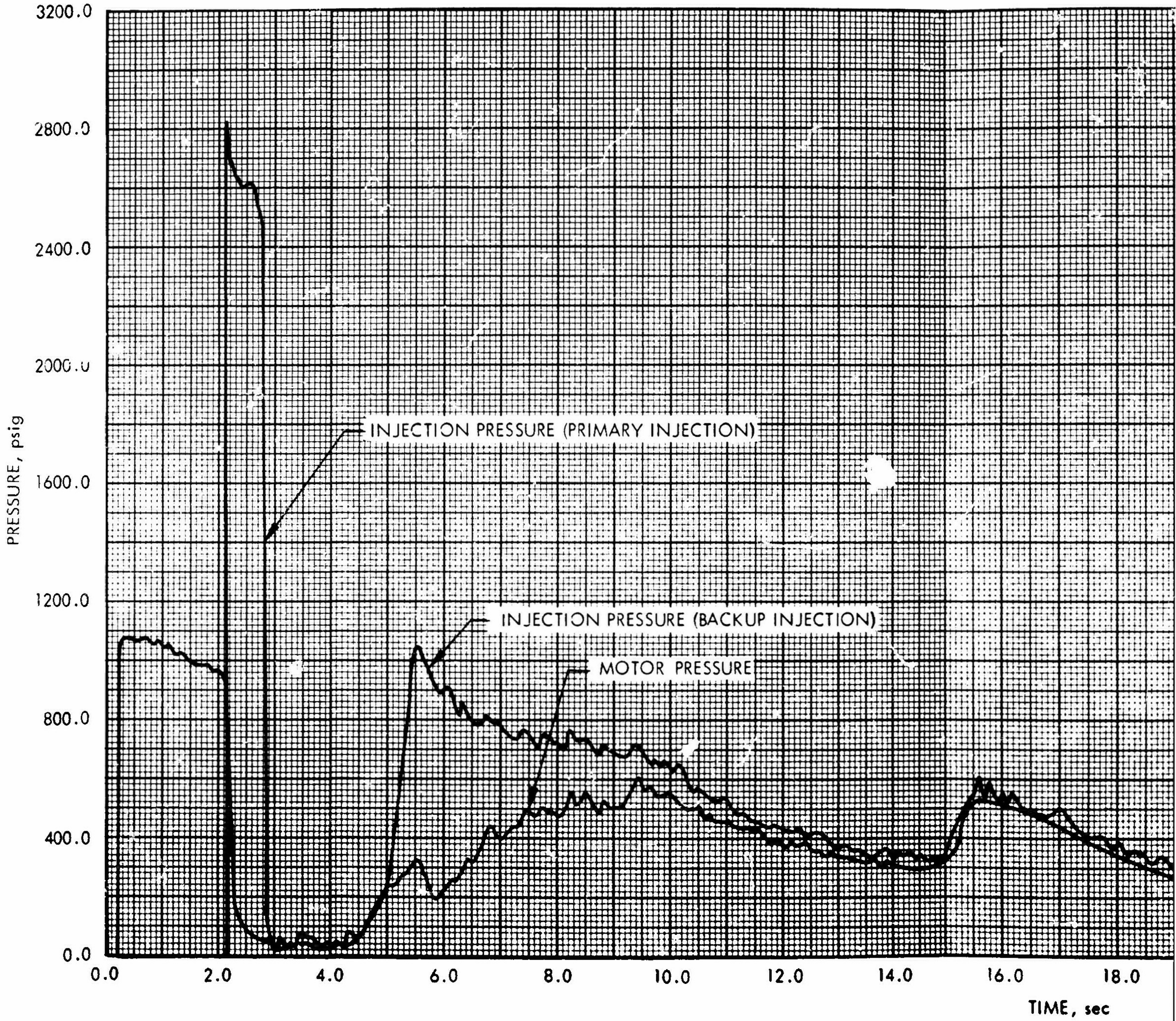
Preparations were then made to conduct tests in motor No. 5. Because the results of the test conducted in motor No. 4 were not conclusive, the grain configuration of motor No. 5 was identical to motor No. 4.

One cold-flow test was conducted to determine the effect of the control rod failure of the previous test. In this cold-flow the control rod was sized to provide a piston travel of 15 in. This resulted in the deflector reaching approximately the same position as reached in the previous motor firing. By then sampling the flow of water through the aft slot, the quantity of water that had been injected into the slot on the previous test could be estimated for comparison with other extinguishment data. In addition, by conducting the test with a short piston travel the effect of the deflector on water dispersion into the aft slot was minimized, and a measure of the effectiveness of the slot design in dispersing the water was obtained.

To preclude the possibility of a rod failure as experienced in the previous test, two changes were made to the injector design. First, a control rod (threaded only as required to attach to the piston and deflector) was used. The rod was polished to a mirror finish to ensure a minimum of friction between the control rod and the swirl plate. Second, the swirl plate was seated in the swirler housing and then tack welded in place. This ensured the correct alignment between the rod and swirl plate throughout the injection period.

In addition to these design changes, particular care was taken in the refurbishment of the injector. All contact surfaces were checked for trueness, hand polished, and then well greased prior to assembly. The cold-flow test configuration was identical to the previous cold-flow test. Spacers were employed between the aft segment and closure to simulate propellant burnback, and a catcher was located at the opening between the flanges to sample the water injected into the slot. High-speed photography was employed to record the injectant flow pattern.

Actuation of the FIKE valve resulted in normal injector response. Visual observation of the test on both the television monitor and the high-speed photos indicated an appreciable amount of water being ejected from the slot. Posttest inspection established that 0.75 lb of water was collected by the catcher, indicating that approximately 14 lb of water, or 17% of the total injectant charge, was dispersed into the slot.



3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
PRESSURE, psig
INJECTION PRESSURE (PRIMARY INJECTION)
INJECTION PRESSURE (BACKUP INJECTION)
MOTOR PRESSURE
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
TIME, sec

A

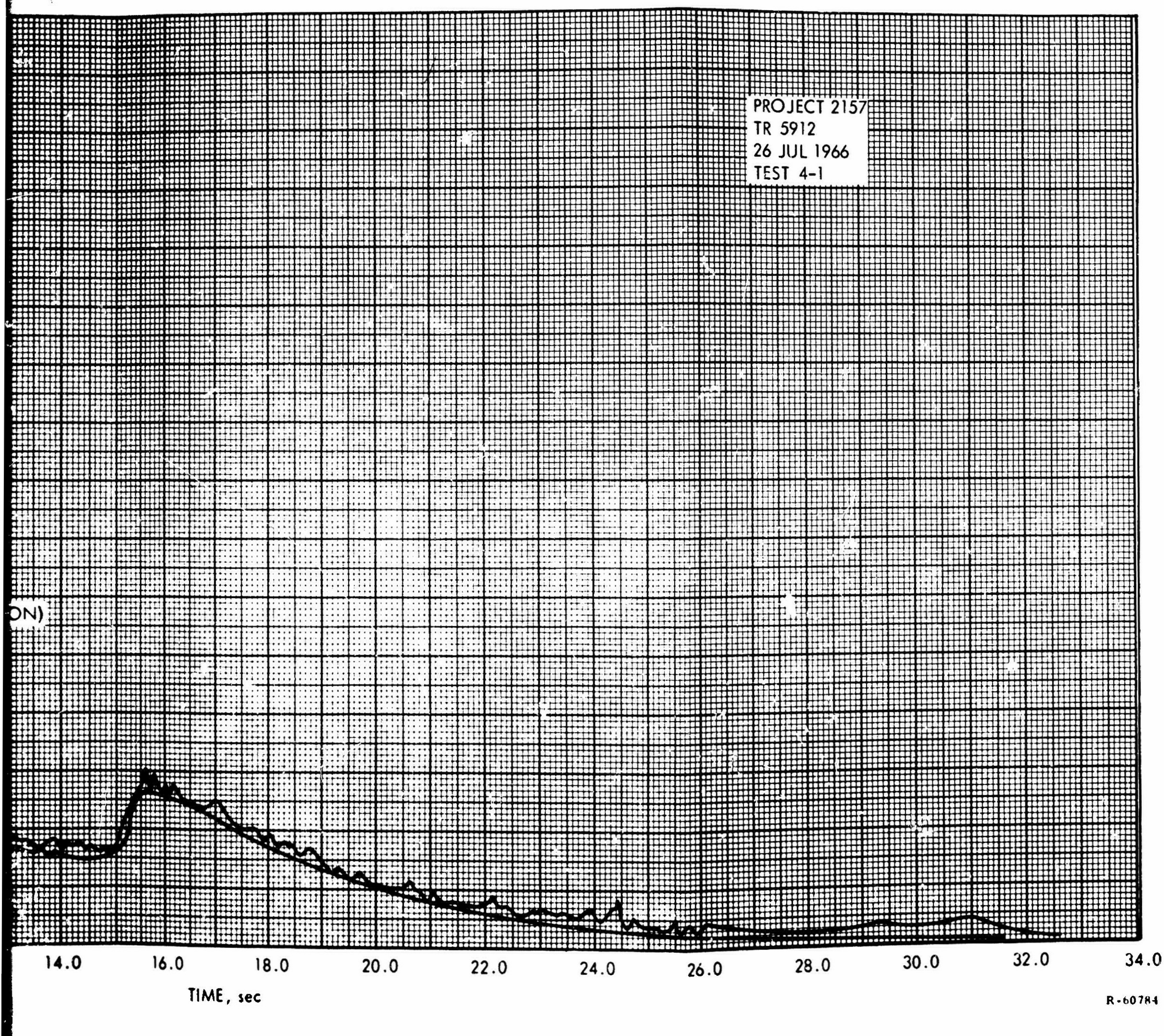
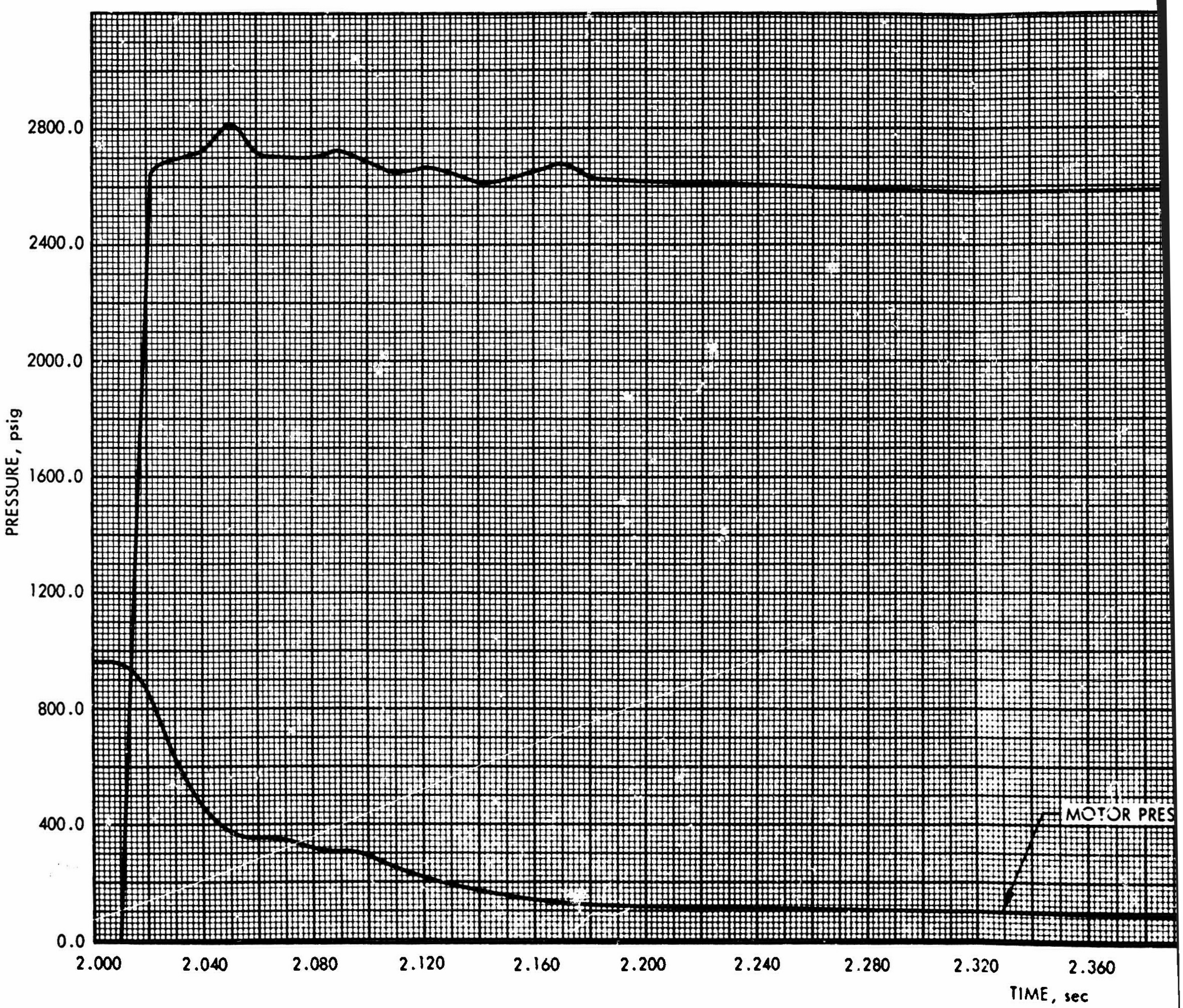


Figure 76. Pressure vs Time Transient, Test 4-1

B



2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
PRESSURE, psig
2.000
2.040
2.080
2.120
2.160
2.200
2.240
2.280
2.320
2.360
TIME, sec
MOTOR PRES

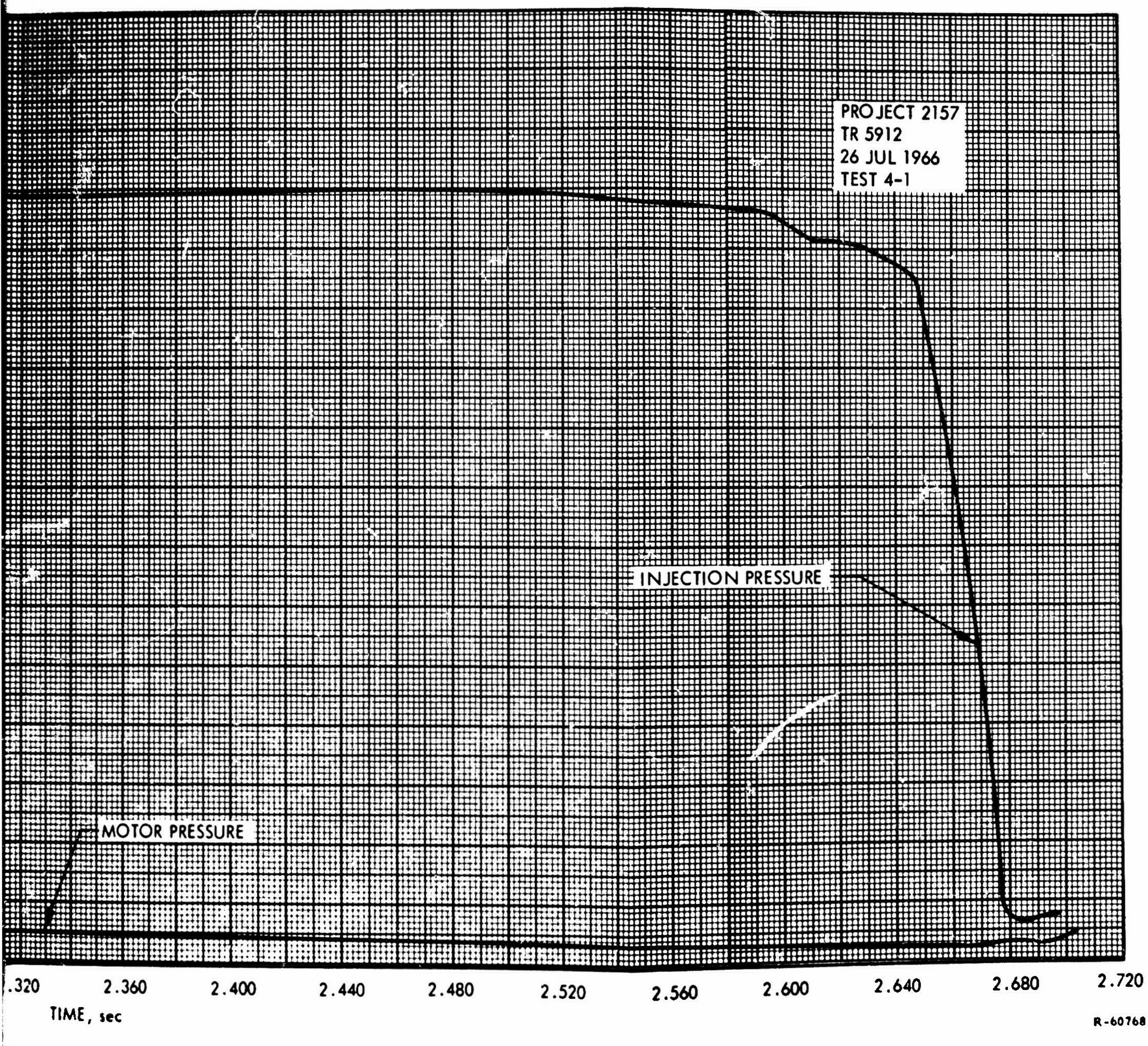


Figure 77. Pressure vs Time Transient, Test 4-1

13

Applying this information to the previous test, it can be calculated that 36.4 lb of water was dispersed into the slot by the primary injector, and 85 lb was injected by the backup injector. By comparing these injection parameters with the parameters for successful extinguishment, it would appear that the primary system alone would have provided sufficient water to extinguish the slot.

The motor was then prepared for an extinguishment test. All excess water was drained from the motor, and the propellant surface was wiped dry and then purged with dry nitrogen.

The injector control rod, sized for 15 in. of piston travel on cold flow, was replaced with a rod sized to provide 39 in. of travel (the maximum travel obtainable with this injector). As discussed previously, this rod was threaded only at the ends and was highly polished over the area in contact with the swirl plate. The injector was loaded with water, and the GN_2 supply was pressurized to provide the maximum injectant flow rate.

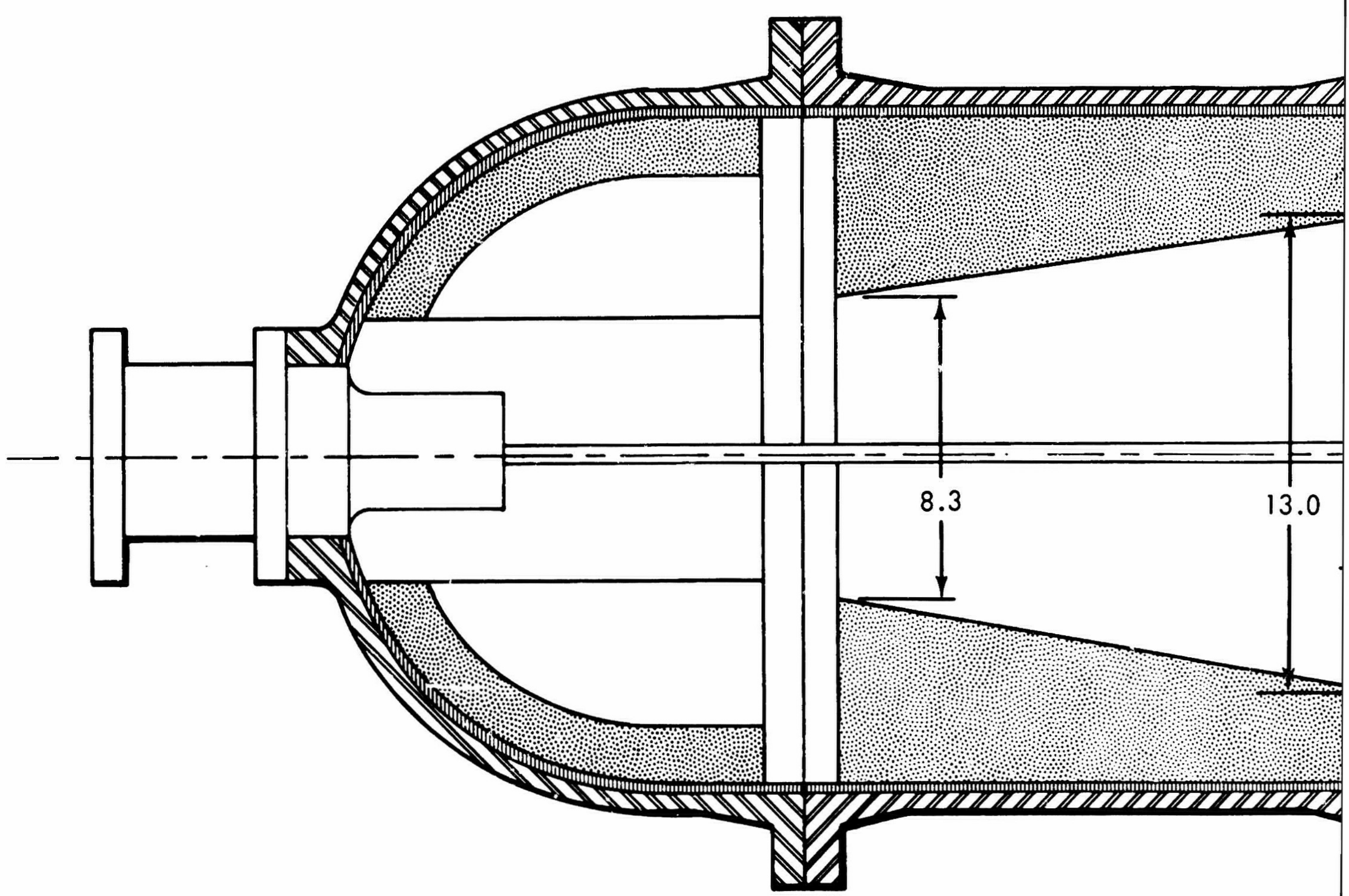
As in motor No. 4, all injection parameters were set to be the maximum capability of the system. The resultant design point is shown as 5-1 in figure 40. The position of the deflector relative to the propellant surfaces at the time of injection is shown in figure 78.

The motor was ignited and allowed to burn for 2 sec before the primary system was actuated. From the visual observation of the test on the television monitor, it appeared that the motor had been nearly extinguished by the primary system. After the normal collapse of the exhaust plume and until the end of the injection phase, there was considerable water and steam being ejected from the nozzle accompanied by many particles of glowing propellant. At the completion of the injection phase, there was a period where there was no visible combustion in the motor.

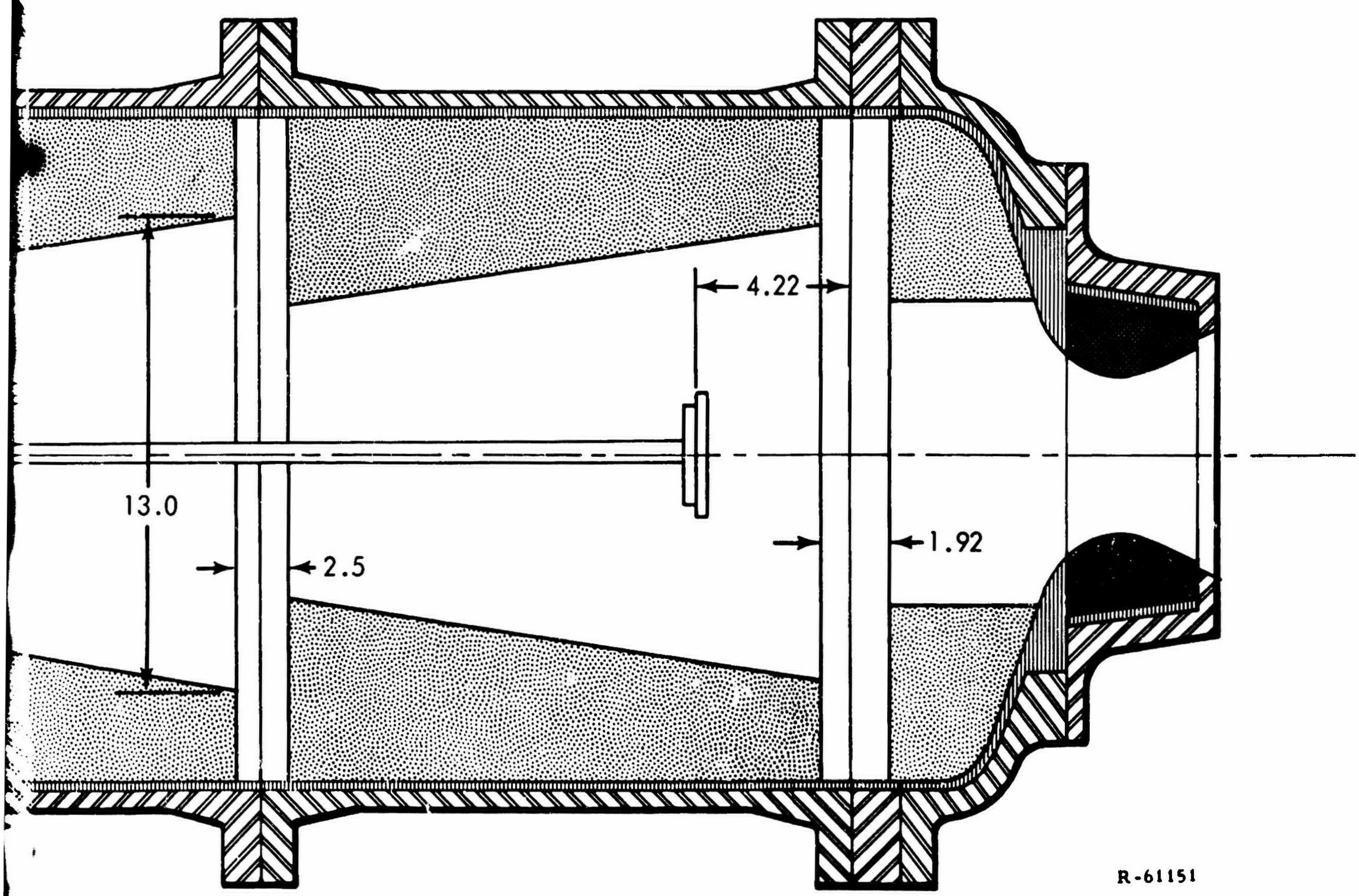
Reignition of the motor then started and flame was visible in the nozzle. The backup system was then actuated; combustion again appeared to be extinguished immediately. During the backup injection period, 500 lb of water was ejected through the motor nozzle followed by expanding GN_2 until the entire backup system had been evacuated to nearly ambient pressure. There was again a period when there was no visible combustion in the motor. Flame then became evident in the motor throat, and reignition took place.

Posttest examination of the pressure data shown in figures 79 and 80 verified that there was a period of approximately 2 sec after primary injection and approximately 7 sec after backup injection when there was no apparent burning in the motor. The pressure increase evident at 8.0 sec was caused by the GN_2 from the backup system flowing into the motor; it was not the result of propellant burning.

At approximately 4 sec after complete reignition of the motor, the inlet line of the backup system failed and the motor exhausted through both the nozzle and the secondary injector inlet until the propellant burnout. Figures 81 and 82 show the area of failure and the resulting damage to the injector.



A



/3

Figure 78. Deflector Position, Relative to the Propellant Surfaces at the Time of Injection, Test 5-1

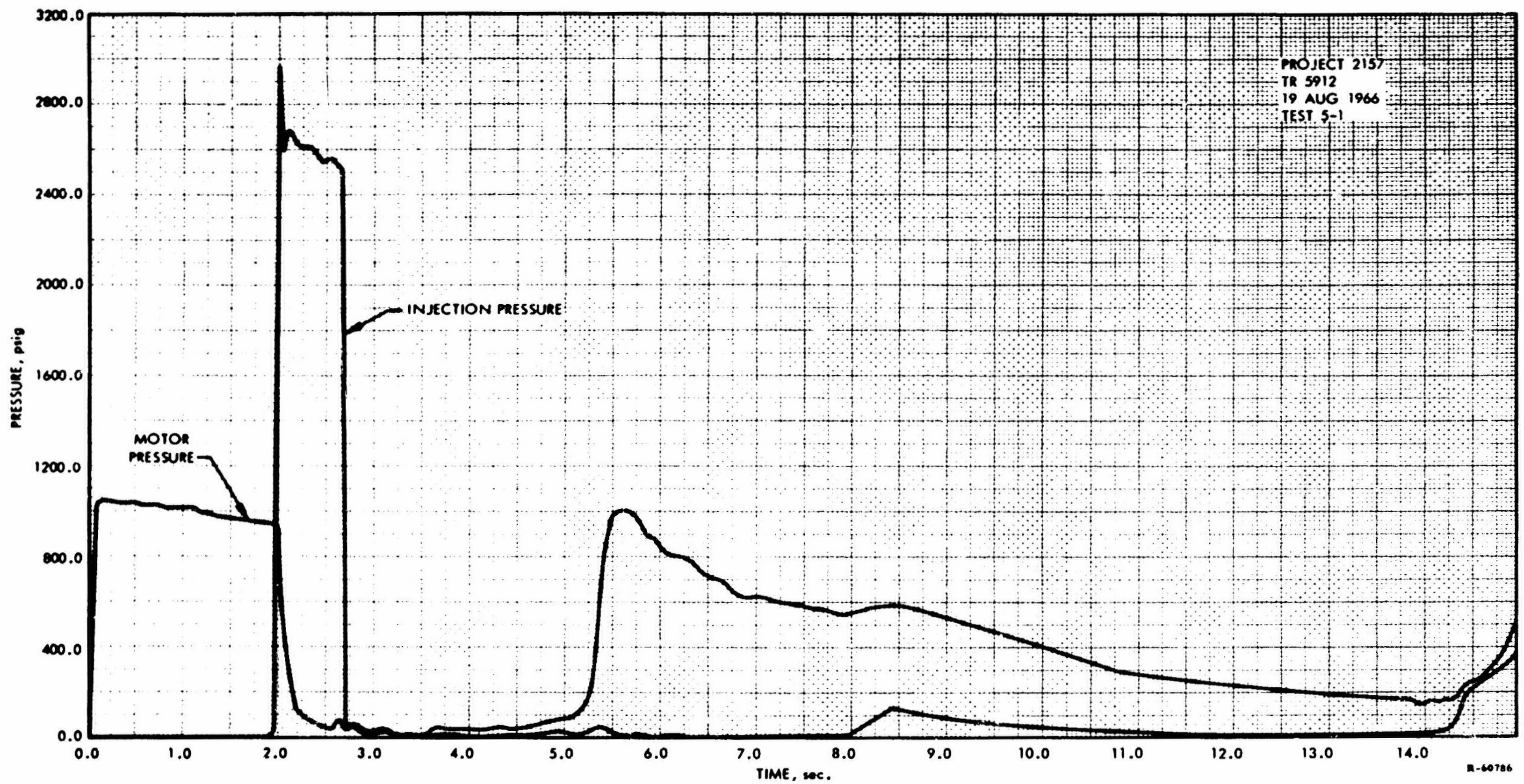
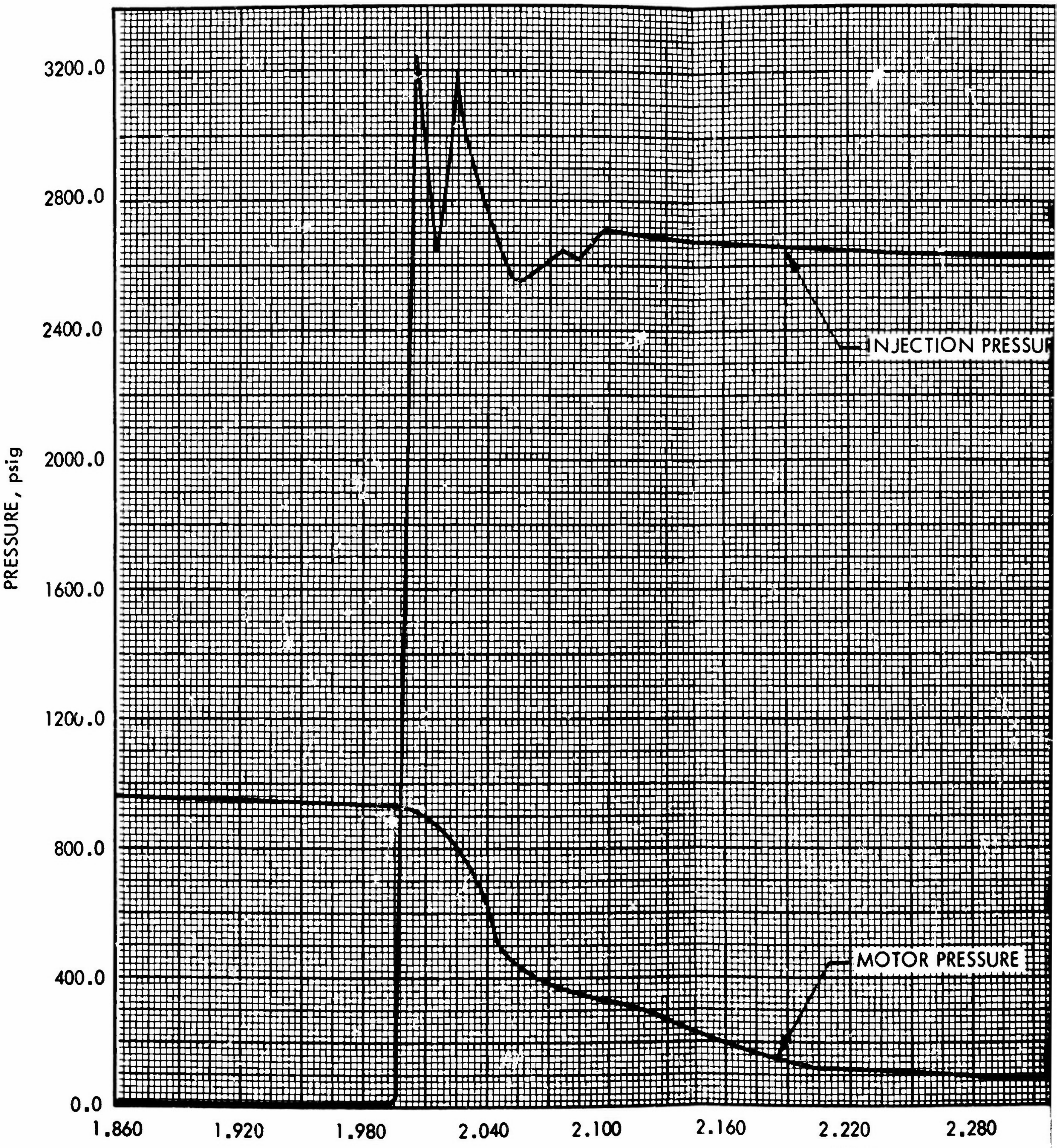


Figure 79. Pressure vs Time Transient, Test 5-1



3200.0
2800.0
2400.0
2000.0
1600.0
1200.0
800.0
400.0
0.0
PRESSURE, psig
INJECTION PRESSUR
MOTOR PRESSURE
1.860
1.920
1.980
2.040
2.100
2.160
2.220
2.280
TIME, sec.

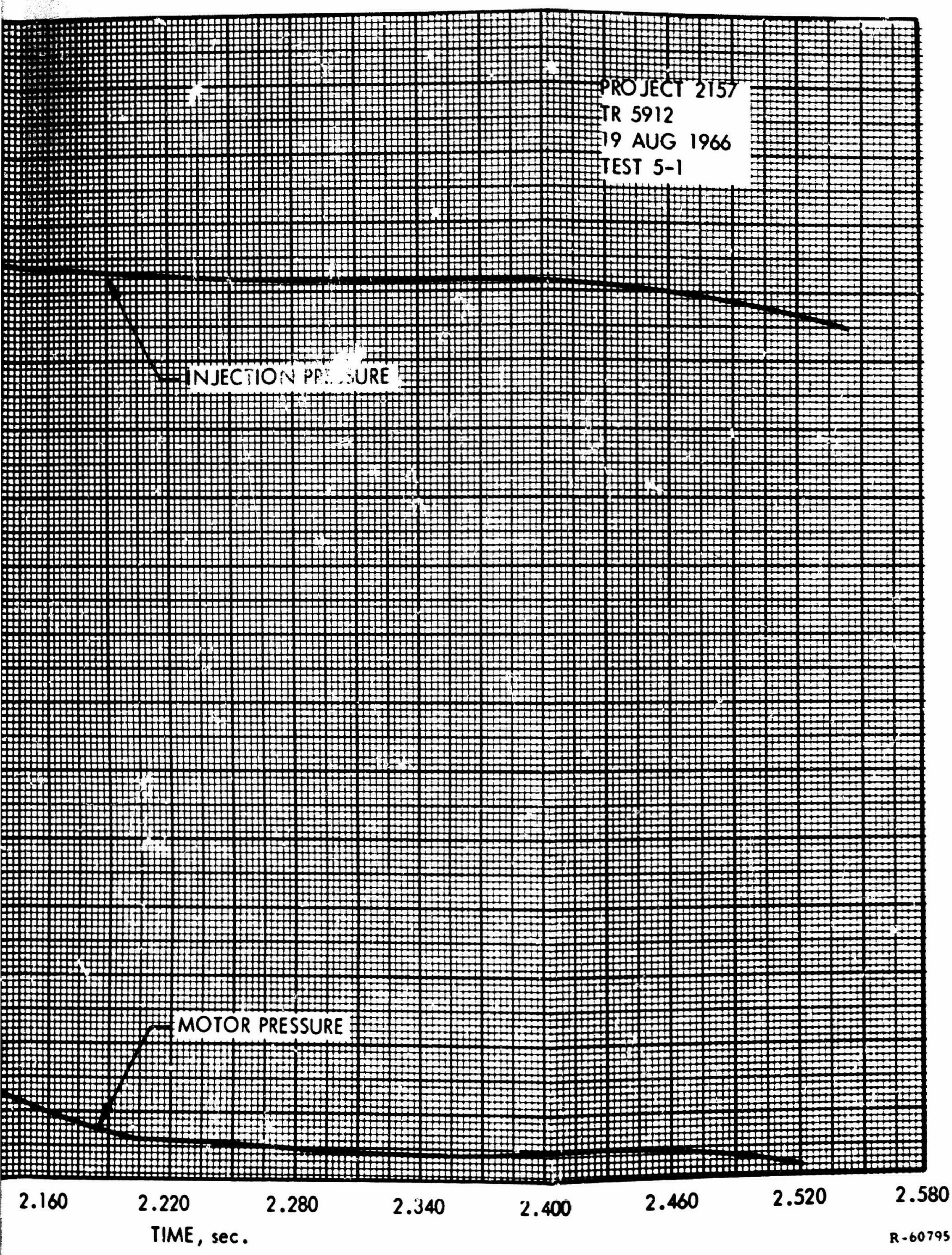


Figure 80. Pressure vs Time Transient, Test 5-1

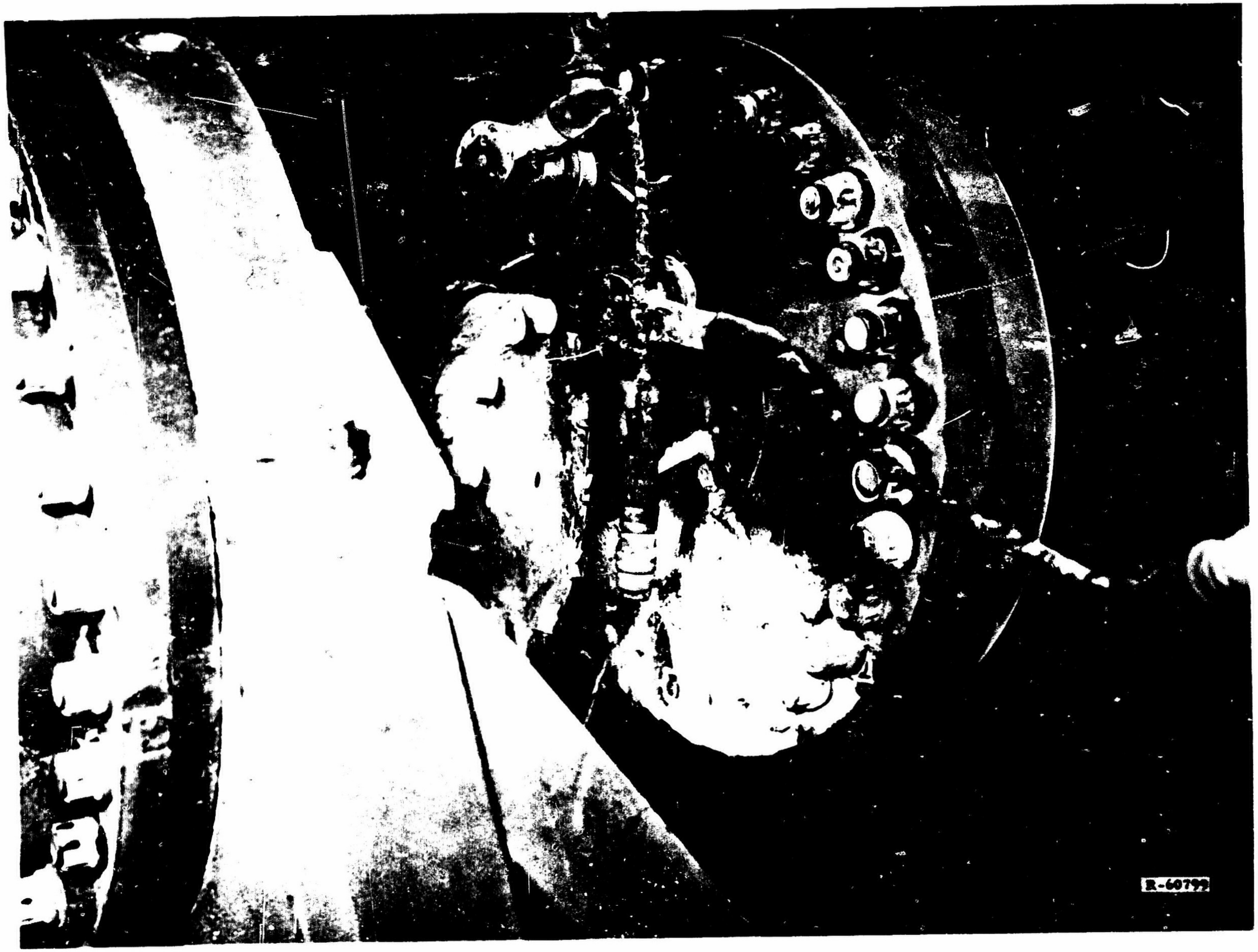


Figure 81. Postfire View of Injector Damage, Test 5-1

Figure 82. Postfire View of Injector Damage, Test 5-1

The cause of failure can be attributed to the backflow of hot combustion products into the uninsulated steel inlet pipe during motor reignition. The resultant overheating of the pipe led to its structural failure and the unrestricted flow of combustion gases through the injector housing.

Previous tests where reignition occurred were not exposed to this backflow condition because reignition occurred before the GN_2 in the backup system had been evacuated.

3.2.4 Analysis of Test Results

Evaluation of the TM-3A test data established the necessity of contacting all propellant burning surfaces with injectant and indicated a substantial scaling factor between the TM-1 and TM-3A size motors.

Correlation of the TM-3A test data by critical injection parameters is shown in figure 83. As in figures 28, 29, and 30 (small motor test results), the areas of complete and incomplete extinguishment are divided by a proposed critical injectant parameter line. On the basis of this line, a scaling factor of approximately 6:1 is indicated between the TM-1 and TM-3A size motors. However, the validity of this critical parameters line is somewhat in doubt because of the internal grain configuration of the motor. The grain configuration utilized in the TM-3A test motors had deep slots between the segments and/or segment and closures. These slots proved to be extremely difficult to contact with injectant, and the instances of reignition may have resulted from inadequate injectant distribution rather than insufficient injectant quantities as indicated by the curve.

A lower limit to the curve was indicated by the results of the backup injection phase of tests 3-2 and 4-1. The lower limit is that flow rate at which combustion would not be terminated regardless of the quantity of water injected. In tests 3-2B and 4-1B, (B denotes the backup injection phase) the motor continued to reignite throughout the injection of water by the backup injection system, indicating that the rate of heat transfer was not sufficient to halt reignition of the propellant surfaces. In these two tests, portions of the propellant were apparently being prevented from burning by the incoming injectant while other areas of the motor burned normally. Posttest examination of the fired hardware indicated that the motor had burned from the aft slot forward.

As expected, motor configuration proved to be an important factor in water distribution. Cold-flow tests using live motors verified this assumption. The first cold-flow test, conducted in a Titan III-C subscale configuration, indicated that a negligible amount of water was being injected into the aft slot. Modification of the grain design to make the slot more

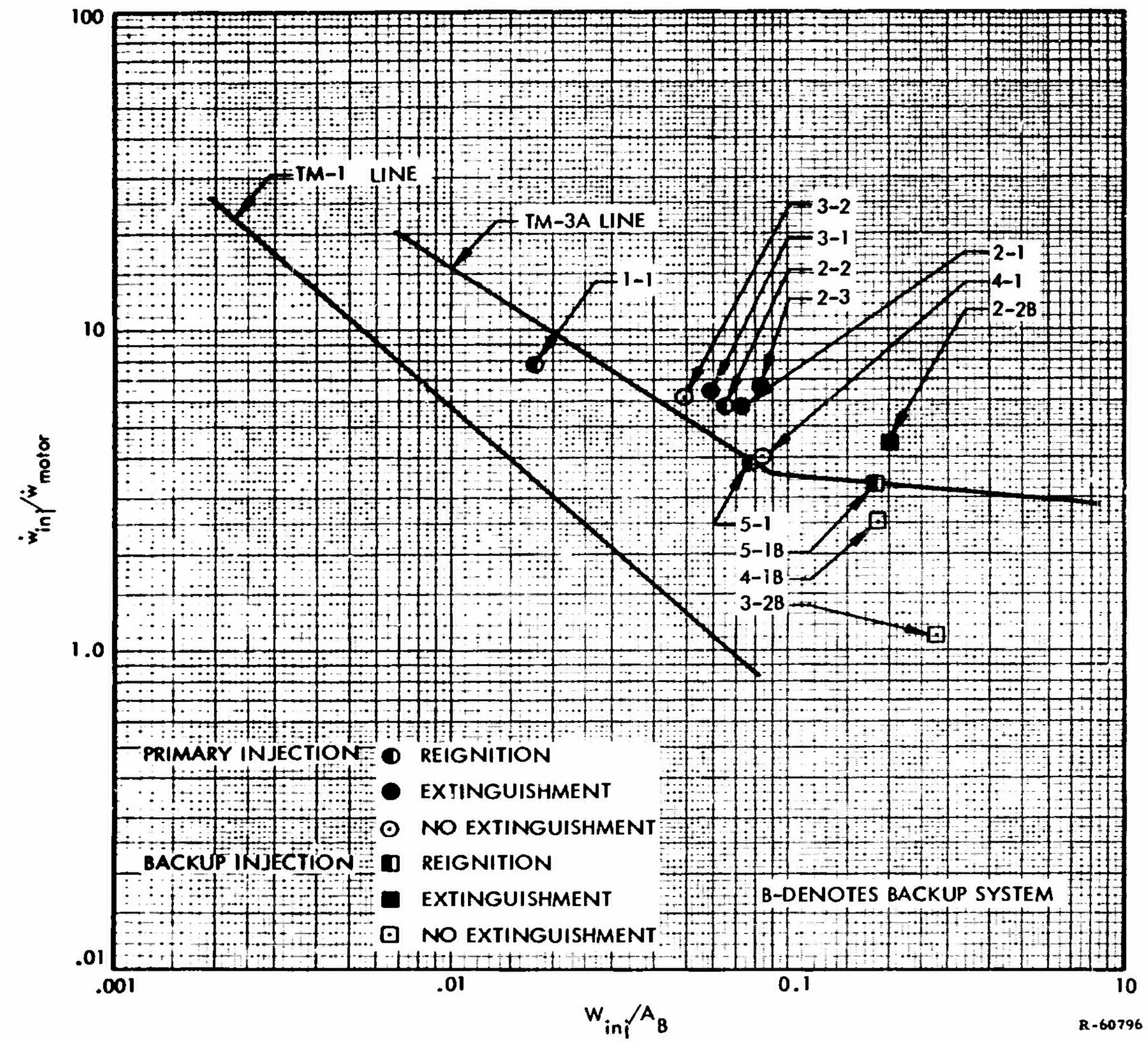


Figure 83. Extinguishment Parameters, TM-3A Test Motor

accessible (motor configuration C00603-04-01), resulted in improved flow into the slot. Approximately 20% of the water injected into the motor flowed into the slot with this motor configuration. Further modifications were made to the grain design to improve water distribution. In motor configuration C00602-05-01, the slot opening was designed to project into the injectant stream and deflect water radially outward to the extremities of the slot. This configuration was found to deflect approximately 30% of the total injectant charge. However, the results of the cold-flow tests were not reflected in the actual motor firings. Considering the aft slot as a separate motor chamber, a flow rate of 50 lb/sec and a charge weight of 8.5 lb should be adequate to extinguish the surface. Considering each of the motor firings on the basis of the cold-flow tests, the design points plot as shown in figure 84. From these considerations, extinguishment of the slot should have been accomplished easily in all motors; however, extinguishment was accomplished in only the 2-1 and 3-1 tests. The obvious explanation is that the mass evolution from the slot during motor combustion has a significant effect on the flow of water down the motor port. This results in the nullification of the dispersing action of both the swirl plate and the deflector.

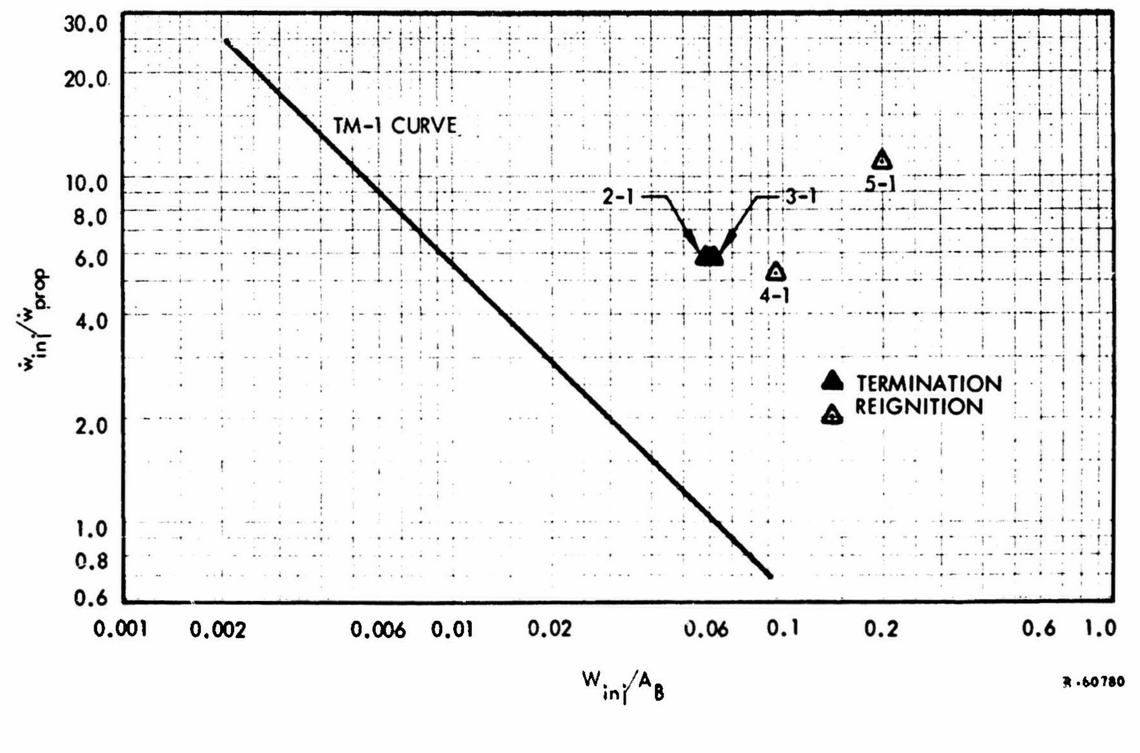


Figure 84. Predicted Flow Parameters at the Motor Aft Slot

The importance of proper slot coverage and its effect on the data presented in figure 84 is evident in a comparison of tests 4-1 and 5-1. These two tests are identical with the exception that in test 4-1, the control rod failed during injection and the deflector was extended to a position only 15 in. down the motor port; in test 5-1, the control rod and deflector were extended 39 in. With the control rod extended 39 in., the deflector was located adjacent to the aft slot causing considerable water to be deflected into the slot. When extended only 15 in., however, the deflector had little effect on flow into the aft slot and coverage of this area was reduced. All other parameters (injectant flow rate and charge weight) were essentially identical. Yet on test No. 4-1, combustion did not appear to be extinguished at any time during injection. Motor pressure data verified that the chamber pressure never dropped below 50 psi. While on test No. 5-1, the motor appeared to be extinguished by both the primary and the secondary systems. Motor pressure data from this test established that the chamber pressure dropped to atmospheric after both the primary and backup injections and final reignition of the motor did not take place until 12 sec after the injection sequence was initiated.

The requirement of contacting all propellant surfaces with injectant establishes the mechanism of combustion termination of PBAN propellants by liquid injection to be one of heat transfer; i. e., the injectant contacts the propellant surface and by heat transfer cools the surface below its autoignition temperature. This was considered to be the mechanism during TM-1 testing when it was found that the pressure drop experienced in extinguishments was often an order of magnitude less than required for extinguishment of PBAN propellant by dp/dt alone. The pressure decay rate required for PBAN extinguishment is in excess of 100,000 psi/sec.

Early laboratory tests also indicated the need for contacting all propellant surfaces. The TM-3A tests verified this assumption. The greatest dp/dt experienced on any test was 54,800 psi/sec on test 1-1 and this motor was not extinguished. The dp/dt on test 3-1, in which the motor was extinguished, was only 10,500 psi/sec, much too low for extinguishment by pressure decay.

As dp/dt is not of apparent importance in extinguishment and heat transfer from the surface is required, it is necessary that the injector is designed to ensure that adequate injectant contacts all propellant surfaces. Any surface, regardless how small, that has not been contacted by injectant will continue burning or reignite and result in total reignition of the motor.

3.3 LARGE MOTOR DEMONSTRATION PHASE

The initial program contract called for the demonstration of a liquid injection technique in a single-segment 120-in.-diameter solid propellant motor. This motor, designated UTC 1201, was scheduled to be ignited and then extinguished a maximum of six times or until extinguishment was not accomplished.

The purpose of these tests was to establish the feasibility of extinguishing a very large solid propellant motor and to verify and refine the design criteria established during the TM-1 and TM-3A tests. In addition, the tests would provide the information necessary for the eventual design of an injection system for a five-segment, 120-in.-diameter solid propellant motor.

Supplemental Agreement No. 2 to the program contract eliminated the requirement for testing the UTC 1201 motor; however, prior to this contract change, considerable effort had been expended in preparation for the test. The following paragraphs will describe this effort in detail.

3.3.1 Motor Design

The design of all motor components was completed. Whenever possible, existing 624A motor designs and hardware were utilized. The final motor design is shown in figure 85.

3.3.1.1 Forward Closure

The forward closure is a standard 624A component. The particular closure scheduled for use on this firing was a residual item from Contract No. AF 04(695)-156 and was insulated and ready for propellant loading when received.

3.3.1.2 Igniter

The igniter is a standard UTC pyrogen igniter used for the ignition of one-segment test motors during the development phase of the 624A Program. Because the injector is located in the normal igniter boss, the igniter was located in the TT port. One of the TT port covers was modified to accept the igniter.

3.3.1.3 Segment

The segment is a standard 624A component. This particular segment was loaded with propellant under Contract No. AF 04(695)-156 and then rejected

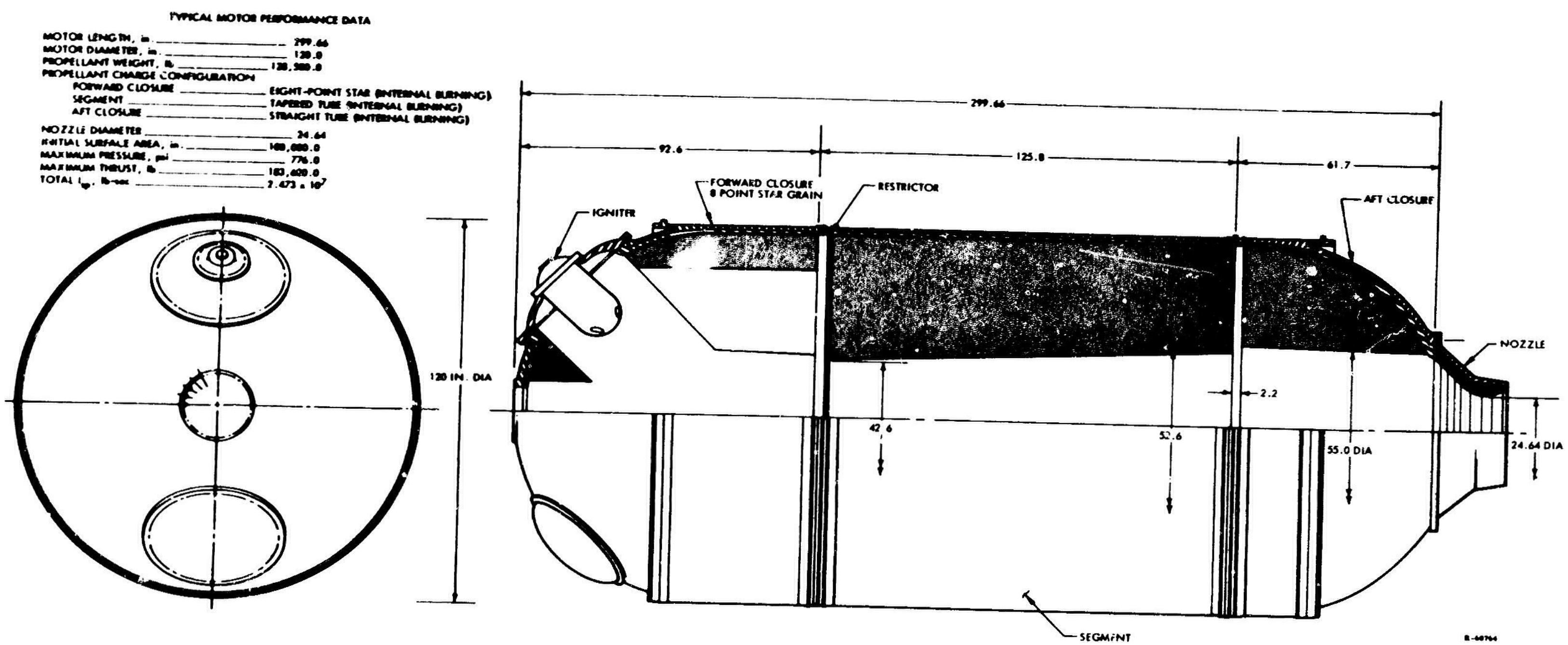


Figure 85. Motor Configuration, UTC 1201

because of an unbonded condition between the propellant and forward restrictor. The discrepant area was repaired by removing the entire restrictor and autoignition strip and then covering the exposed propellant with a layer of A1-60 liner. A restrictor was then scheduled to be bonded to the liner; however, this was not accomplished before the contract change. A comparison of the original and repaired segment is shown in figure 86.

3.3.1.4 Aft Closure

The aft closure is a standard 624A component with the exception of the insulation, which was modified to meet the particular requirements of this test. The plastic insert used at the nozzle entrance on the standard design was eliminated and the entrance area was built up with additional insulation. This change, shown in figure 87, was made to conserve costs.

3.3.1.5 Nozzle

An entirely new nozzle was designed for this test. This nozzle (shown in figure 88) consisted of a one-piece AISI 4130 steel housing insulated in the entrance and throat areas with graphite phenolic. Graphite-phenolic was selected as the throat material on the basis of its high resistance to thermal shock (the thermal shock resulting from injecting water into the motor is one of the most severe nozzle environments), and the fact that phenolic-graphite nozzle rings were available as residual material on Contract AF 04(695)-156. The exit portion of the nozzle was terminated at an area ratio of 1.15 to minimize nozzle costs and to reduce the motor thrust.

The nozzle design was completed and vendor fabrication quotes were received, but fabrication had not been started at the time of the contract change.

3.3.2 Injection System

A preliminary design of the injector was completed. This design was generated prior to the TM-3A motor tests and therefore does not reflect some of the problems encountered on this test series.

The proposed injection system, shown in figure 89, utilized a pintle-type injector operated by a hydraulic cylinder and an ullage-pressurized water supply.

The injector was similar in design to those tested in the TM-1 and TM-3A test programs. The primary difference being that the pintle travel, both distance and rate, was controlled by a remotely operated hydraulic system. With this system, the pintle is allowed to move forward, initiating the injection cycle by releasing the pressure in the hydraulic cylinder.

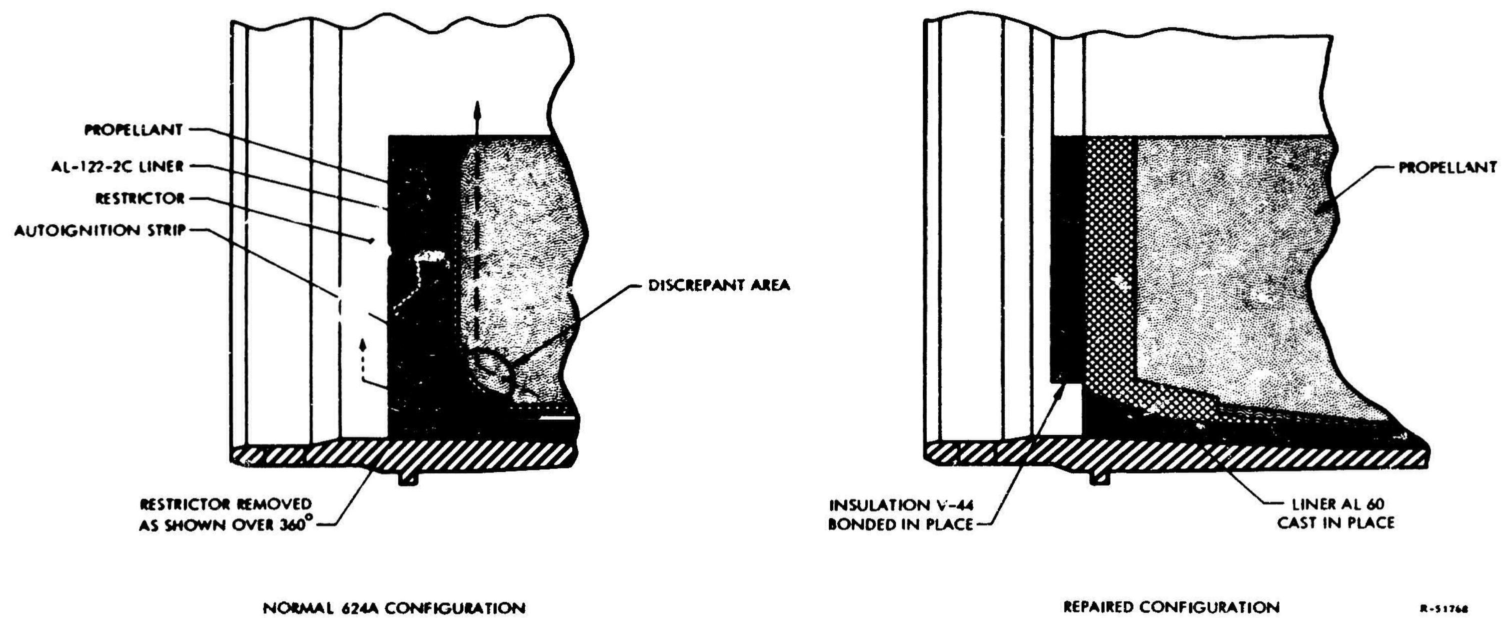


Figure 86. Details of the Segment Repair

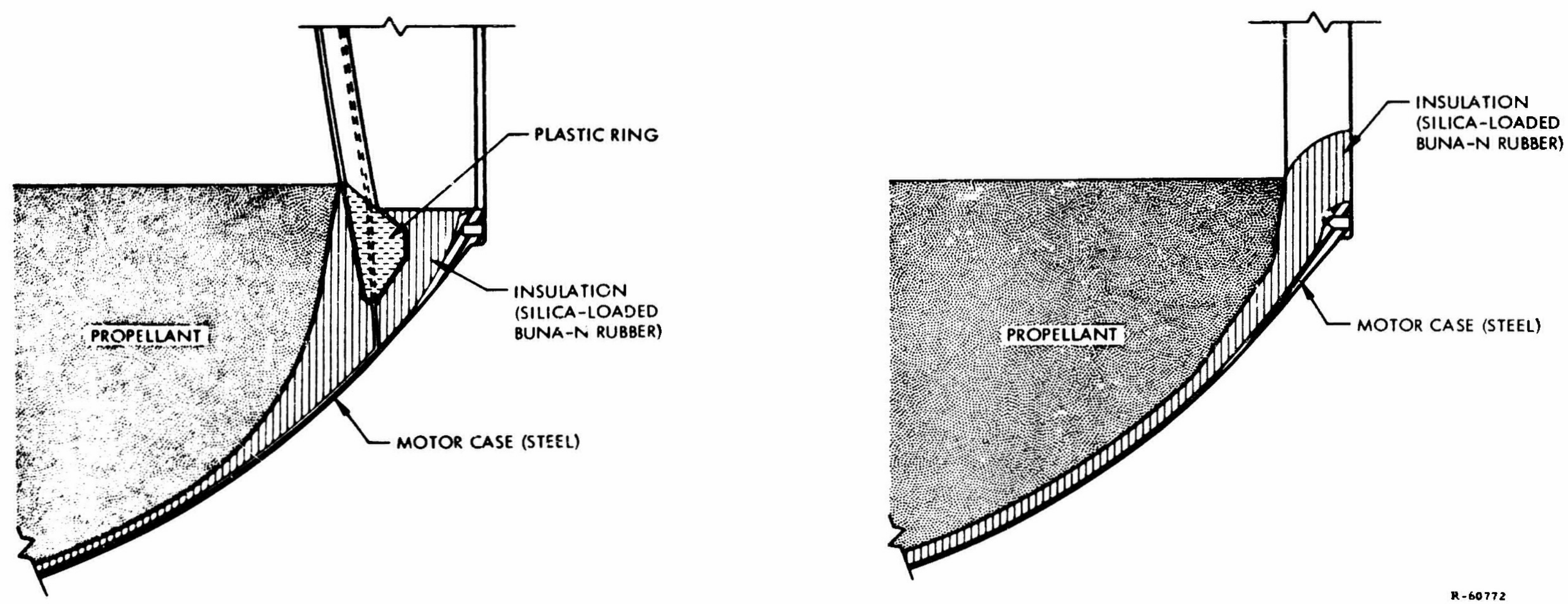


Figure 87. Aft Closure Modification

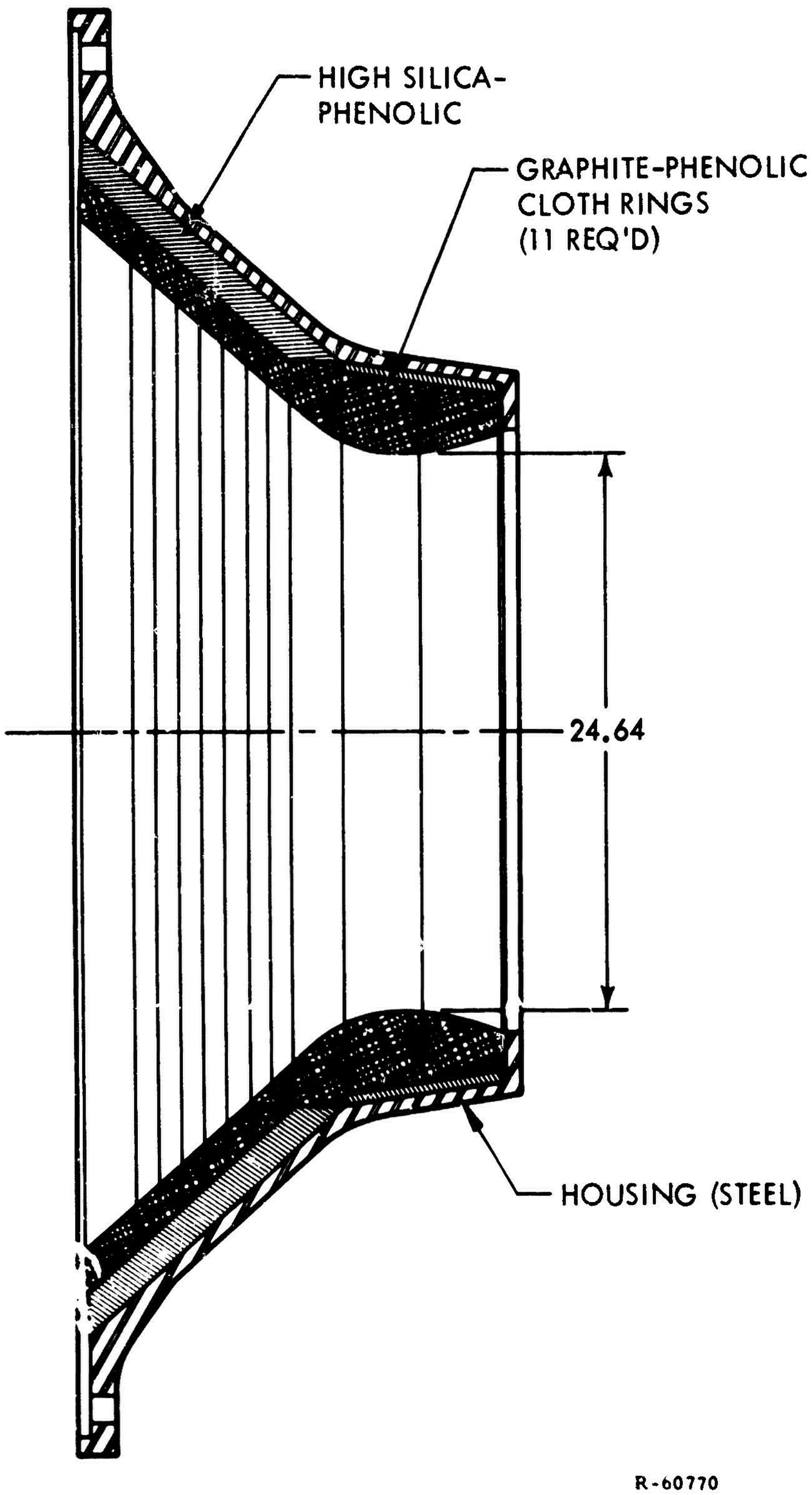


Figure 88. Nozzle, 1201 Motor

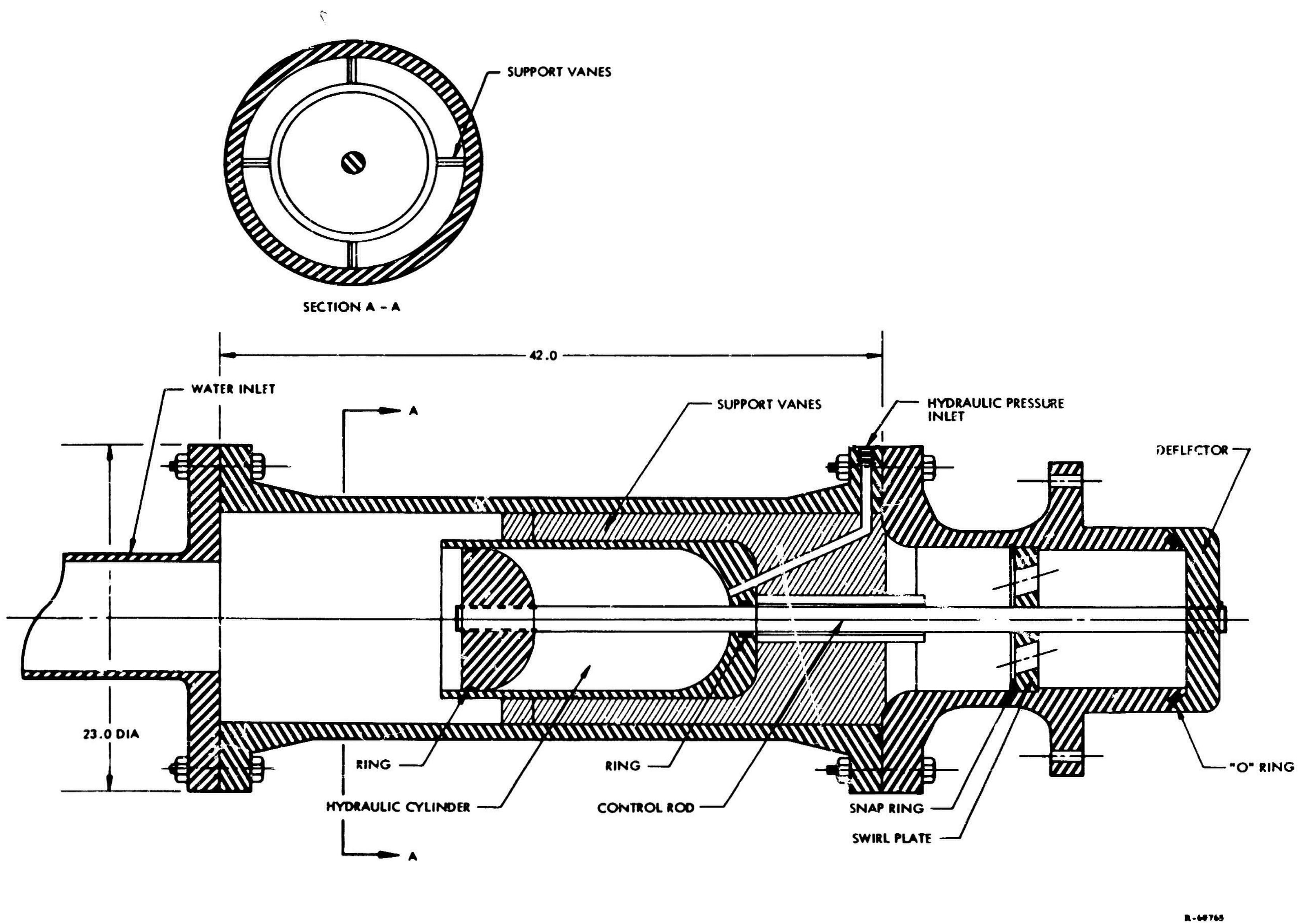


Figure 89. Injection System, 1201 Test Motor

Rate of movement is controlled by a variable orifice. The pintle was then returned, thereby closing the injector to motor backflow, again by pressurizing the hydraulic cylinder.

An ullage-pressurized water supply was used in place of the positive displacement cylinder solely on the basis of size considerations. Preliminary calculations of water requirements indicated a flow rate of 8, 000 lb/sec and a water charge weight of 4, 500 lb. Based on the TM-3A injector design, the 1201 injection system would require a cylinder 36 in. in diameter and 120 in. long. Fabrication of such a cylinder which would be capable of operation at 3, 500 psi was not economically feasible.

Thrust vector control pressurization tanks used on the Titan III-C SRM would be utilized as water tanks. A schematic of the proposed system is shown on figure 90.

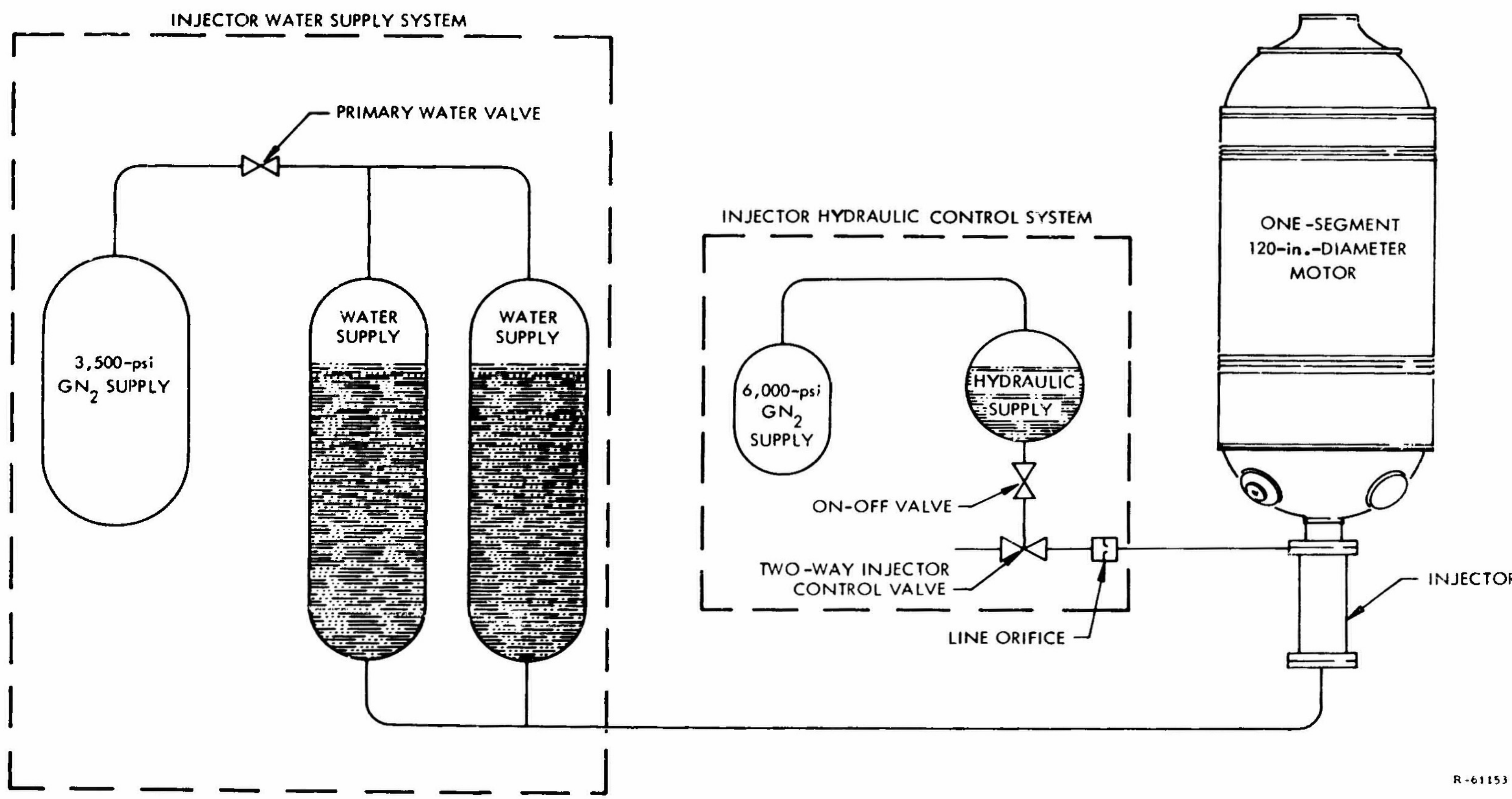


Figure 90. Injector System Schematic, 1201 Test Motor

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

In conclusion, it was established that solid propellant motors cast with PBAN propellant could by extingushed by injecting a liquid into the combustion chamber. The development of a reliable system for extinguishing motors with radial slots, such as the Titan III-C configuration, was however not accomplished.

Extinguishment of the propellant was determined to be accomplished by rapidly lowering the surface temperature of the propellant until it could no longer sustain combustion. The controlling process of extinguishment proved to be heat transfer between the injectant and the propellant surface and products of combustion.

Therefore, because of the high heat capacity of water, it proved to be an effective injectant if uniformly dispersed over all burning surfaces in the motor. However, any surface that was not contacted by injectant and properly cooled was found to reignite and result in the eventual reignition of the entire motor.

Motor with slots, as exist between the segments of the Titan III-C motor configuration, therefore proved to be particularly difficult to extinguish.

Propellant quality also plays an important part in extinguishment. Voids, cracks, or other irregularities in the propellant, if exposed at the instant of extinguishment, can present burning surfaces that cannot be contacted with injectant and will subsequently lead to reignition of the motor.

Combustion termination by liquid injection remains an attractive means of providing extinguishment of certain solid propellant motors. Motor with grain designs utilizing internal burning cylindrical or star ports should be easily extinguished by a simple head-end injector. Segmented motors having burning radial slots require a more sophisticated injector capable of directing injectant into to each slot. However, considerable effort must be spent on basic research before the technique can be reliably used in an operational motor. This effort should be directed as follows:

A. Establish an analytical model of the combustion process.

B. Verify and expand the design parameter curves presented in this report to provide a tool for injector design. Motors used

in these tests should be identical in configuration and should have no slots or other hard-to-contact surfaces.

C. Determine the effect of propellant irregularities on the extinguishment process and establish quality levels required in motors where extinguishment is required.

Design of an injection system for a particular motor configuration could then be directed toward the specific problem of providing an injector capable of contacting all propellant surfaces.

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APPENDIX I

INSTRUMENTATION RESPONSE REQUIREMENTS FOR COMBUSTION TERMINATION STUDIES

1.0 INTRODUCTION

Combustion termination studies conducted at UTC have demonstrated that termination is characterized by rapid pressure changes in the combustion chamber. Laboratory studies have shown that the susceptibility of a particular propellant formulation to complete termination can be characterized by the maximum rate of pressure decay imposed upon the combustion chamber. Typically, these rates can be as high as 150,000 psi/sec. Accurate determination of these rates required careful consideration of the dynamic response characteristics of the pressure-measuring instrumentation. The calculations in this analysis were made to define the dynamic response characteristics required for such instrumentation.

2.0 DISCUSSION

Characterization of the combustion termination properties of solid propellants is usually determined by suddenly increasing the exhaust nozzle area in a combustion chamber. From an analysis of the ballistics of such a step change in nozzle area, the pressure decays exponentially with time. Typically, the instrumentation used in these experiments is a diaphragm transducer and an optical recording galvanometer, such as a CEC system. Therefore, the response of this instrumentation can be obtained by studying the solution of the equation:*

$$\frac{d^2y}{d\tau^2} + \frac{(2h)\,dy}{d\tau} + y = \exp\left[\frac{-\lambda t\tau}{2\pi f_n}\right] \qquad (1)$$

where

- y = dimensionless deflection; i.e., P/Po
- P = chamber pressure
- Po = steady-state pressure
- h = fraction of critical damping
- f_n = natural frequency of the instrumentation

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* For example, see CEC Manual on Galvanometer Characteristics.

λ_t = true exponential decay constant of the pressure; i.e., $P/Po = \exp(-\lambda_t t)$

τ = dimensionless time ($\tau = 2\pi f_n t$)

t = real time.

In the analysis of pressure decay rates, the maximum rate of pressure decay experienced by the propellant must be determined. From the ballistics of the experiment, the maximum pressure decay rate is given by:

$$\left(\frac{dP}{dt}\right)_{max\ theo} = -\lambda_t Po \tag{2}$$

or

$$\left(\frac{dy}{d\tau}\right)_{max\ theo} = \frac{-\lambda_t}{2\pi f_n} \tag{3}$$

Thus, the maximum pressure decay rate in the combustion chamber is obtained the instant the nozzle area is increased. However, the inertia of the instrumentation prevents the system from following this sudden change in pressure. Therefore, the problem is to determine the relation between the maximum decay rate experienced by the propellant and the maximum measured decay rate; e.g., how do the dynamics of the instrumentation and the ballistics affect the measured rates. Mathematically, this becomes:

$$\left(\frac{dy}{d\tau}\right)_{max} \Big/ 2\pi f_n = \frac{-\lambda max}{\lambda t} = f(\lambda t,\ 2\pi f_n,\ h) \tag{4}$$

Equation 1 has been solved using the TR-48 analog computer to determine the functional behavior of equation 4. The results are presented in figure 91 in the form $\lambda max/\lambda t$ vs $\lambda t/2\pi f_n$ for various percentages of the critical damping; 64% being the typical value in most systems. These results show that for a 10% maximum error in the measured pressure decay rate:

$$f_n > 1.93\ \lambda_t \quad \text{for 64\% damping}$$

For example, if the expected depressurization rate is 150,000 psi/sec at 500 psi then:

$$\lambda_t = 300\ sec^{-1}$$

and f_n of the instrumentation must be greater than 580 cps for a 10% error in the measured rate. Thus, these results can be used to design instrumentation systems for combustion termination experiments.

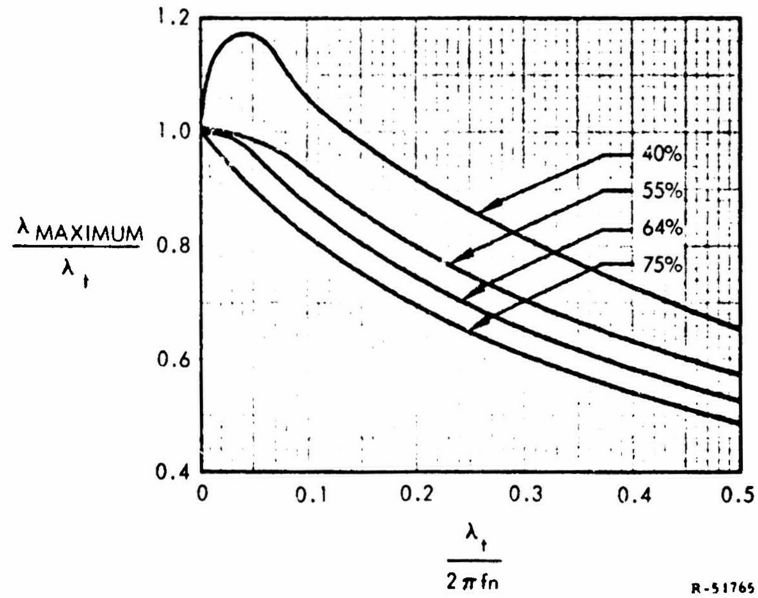

Figure 91. Response of Second Order Instrumentation to Exponential Forcing Function, Parameter As Percent Critical Damping

These calculations can also be used to correct measured depressurization rates for instrumentation lag errors. To do this, figure 91 has been crossplotted to give $\lambda max/\lambda t$ as a function of $\lambda max/2\pi f_n$ for various values of h. This crossplot is shown in figure 92.

As shown in figure 92, the error in the pressure decay measurement can change significantly with the change in experimental decay rate. In other words, the percentage error varies by a factor of two for a two to one change in experimental rate. During analysis of the data, these changes could significantly affect the accuracy of the results.

3.0 CONCLUSIONS

The instrumentation configuration used on the TM-1 motors has a natural frequency (fn) of 430 cps, and the maximum value of λmax observed to date is 60 sec^{-1}. As shown by figure 92, the error in the measured depressurization rates resulting from instrumentation lags in less than 3%.

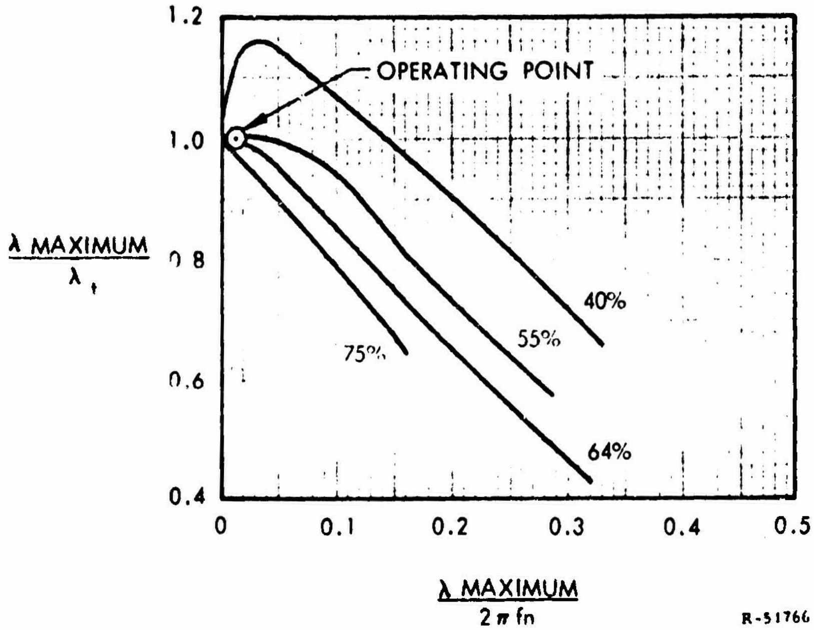

Figure 92. Instrumentation Error in Exponential Decay Rate Measurements, Parameter As Percent Critical Damping

The calculations presented in figures 91 and 92 also show that some care must be exercised in the design of instrumentation and interpretation of pressure decay rate measurements for combustion termination experiments. Considerable errors may result if the effects of inertia on the instrumentation are not carefully considered.

APPENDIX II

MAXIMUM POSSIBLE OVERPRESSURE DURING COMBUSTION TERMINATION BY FLUID INJECTION

1.0 INTRODUCTION

Under Air Force Contract No. AF 04(695)-845, UTC is conducting a program to demonstrate the feasibility of terminating a 120-in.-diameter motor by fluid injection. If the injected fluid fails to terminate propellant combustion, significant overpressures could be generated in the motor, resulting in structural failure of the motor case. The magnitude of the maximum overpressure depends on the rate of injection and the thermodynamic properties of the injectant. Therefore, the consideration in the selection of the injection fluid and the injection rate is the maximum overpressure which could be generated.

A series of calculations were made to determine the maximum magnitude of the potential overpressures for a series of fluids which have been considered for use. These fluids included water, Freon 22, and nitrogen tetroxide (N_2O_4). Water was considered because it has a high heat of vaporization and has been successfully used in smaller motors. Freon 22 and N_2O_4 were studied because these fluids are currently used as TVC fluids and are readily available in the test stand.

2.0 SUMMARY

The results of these calculations showed that for reasonable injection rates, water would generate a maximum pressure somewhat less than twice the operating pressure. For Freon 22, the pressure increase could be as high as three times the normal operating pressure, and for N_2O_4, three and one-half times the normal operating pressure.

3.0 DISCUSSION

The maximum overpressure in the motor occurs if all the injected fluid is vaporized, if none of the burning propellant surface is extinguished, and if the resulting mixture of injected fluid and propellant combustion products reach thermodynamic equilibrium in the motor. Under these

conditions, the chamber pressure will increase, causing the propellant burning rate to increase, thereby producing an additional increase in the chamber pressure.

The exact calculation of these effects is extremely complex. However, reasonable estimates of the maximum overpressure can be obtained using the following assumptions:

A. Chemical equilibrium is established between the injected fluid and the propellant combustion products. Kinetic limitations tend to reduce the overpressure and are only important at very low chamber temperatures.

B. The propellant burning rate follows the normal steady-state relation. In effect, this assumption states that the propelland burning rate is independent of the flame temperature of the mixed gases (injected fluid plus propellant combustion products).

C. The flame temperature of the mixed gases at equilibrium is independent of pressure.

With these assumptions, the pressure increase can be calculated using the equations:

$$\left(\frac{P_c}{P_{c_o}}\right)^{1-n} = \frac{c^*}{c^*_o}\left(\frac{\dot{M}_w}{\dot{M}_p} + 1\right) \tag{1}$$

$$\frac{c^*}{c^*_o} = f\left(\frac{\dot{M}_w}{\dot{M}_p}\right) \tag{2}$$

$$\frac{\dot{M}_w}{\dot{M}_{p_o}} = \frac{\dot{M}_w}{\dot{M}_p}\left(\frac{P_c}{P_{c_o}}\right)^n \tag{3}$$

where

M_w = injectant flow rate

$\dot{M}_p$ = propellant mass flow rate

n = burning rate pressure exponent

P_c = chamber pressure

c^* = characteristic velocity

o = subscript to represent corresponding values with no fluid injection.

The curves shown in figure 93 were calculated for water, Freon 22, and N_2O_4 in combination with propellant UTP-3001. The solid line represents the results when water is used. Complete thermodynamic equilibrium over the entire range of injection ratios was assumed in these calculations. The single-dashed line represents the same calculations for mixtures with Freon 22, and the double-dashed line represents the results for N_2O_4 mixtures.

In the case of water with an injection ratio greater than 1.4, the equilibrium chamber temperature is less than 1,000° K. Under these conditions, the principal chemical species present are H_2O, H_2, CH_4, CO, and CO_2. Because kinetic limitations for these chemical species can be expected at this low temperature, a second calculation for water injection was made assuming frozen equilibrium at temperatures below 1,000° K. These calculations are represented by the triple-dashed line in figure 93.

In the case of Freon 22 and N_2O_4, the calculated chamber temperatures were always greater than 1,700° K. Kinetic limitations would not be expected under these conditions; therefore, frozen equilibrium calculations are not appropriate for these fluids.

4.0 CONCLUSIONS

From the results shown in figure 93, it is apparent that the lowest overpressures are generated by the injection of water into the chamber. It is reasonable to expect maximum possible overpressures of 1.90 with water, or 1.75 if the kinetic limitations are significant. When applied to the 1205 motor (maximum chamber pressure 700 psi, case burst pressure 1,200 psi), there is a possibility of overpressurizing the motor case during the initial operation of the motor. However, chamber pressure is regressive in the 120-in. motor. After 25 sec the pressure drops to a point where case failure should not occur, even under the worst possible conditions.

Figure 93 also shows that failure to terminate combustion with Freon 22 or N_2O_4 can produce chamber pressures far in excess of safe operating limits.

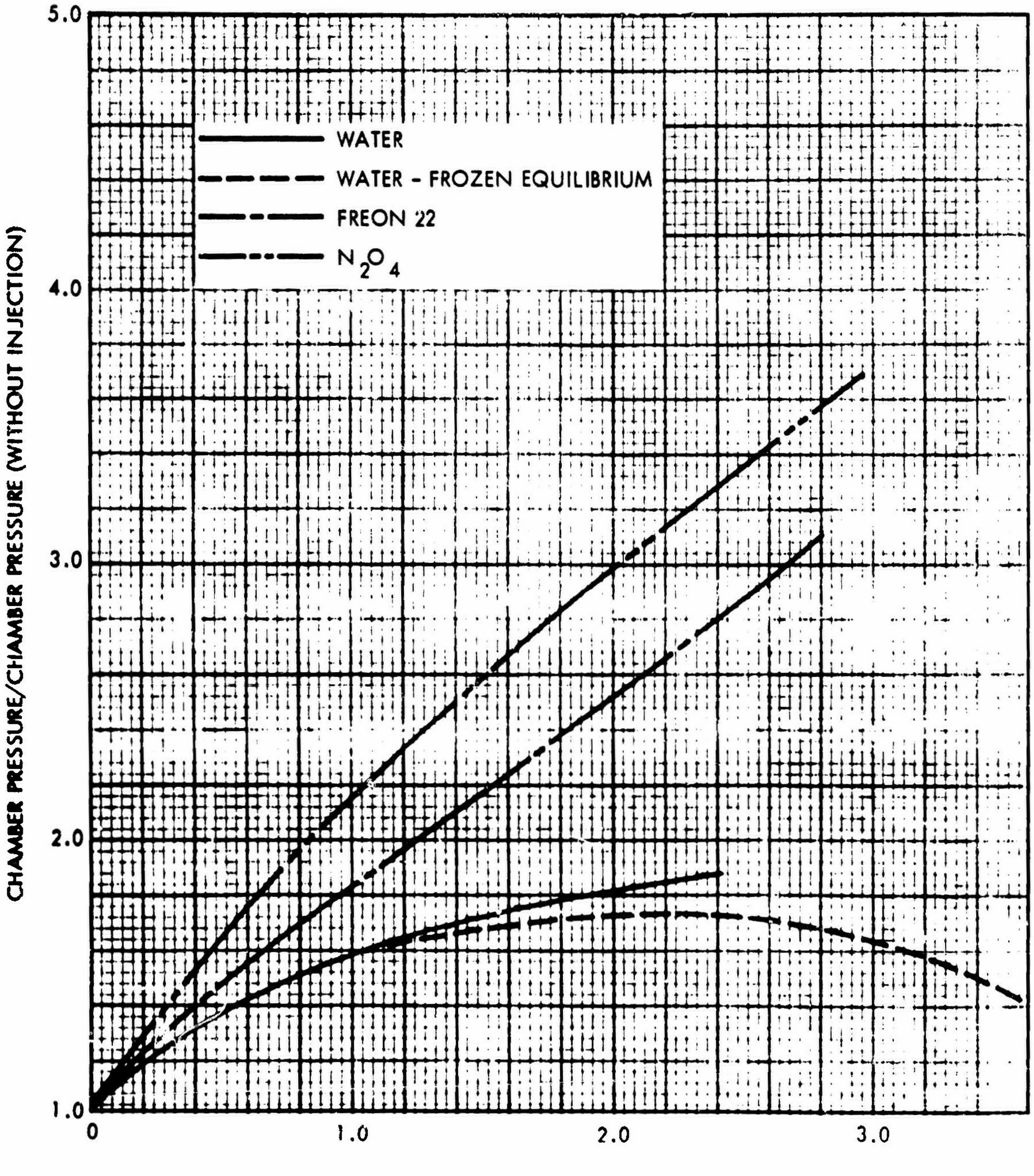

Figure 93. Chamber Pressure Increase as a Result of Fluid Injection

These results suggest that minimum overpressures occur when using fluids which are chemically inert or fuel rich and which have a high heat of vaporization. Therefore, the addition of salts such as NH_4Cl or LiCl to water offers the possibility of reducing the maximum possible overpressure in the motor. These salts have heats of sublimation of the order of 800 cal/g, compared to 500 cal/g for water, and have sublimation temperatures approximately 1,500° K below the propellant flame temperature.

In addition, the small-motor test results indicate that the range of practical flow rate ratios is 3.2 to 7.0. Under these conditions, the maximum possible overpressures, obtained by extrapolating the curve for water shown in figure 93, are considerably less than 1.75. Therefore, the maximum overpressure under actual test conditions might be on the order of 1,000 psi.

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13. ABSTRACT

This is the final report covering the experimental and analytical work performed by UTC on Air Force Contract AF 04(695)-845. The original purpose of the program was to develop a liquid injection combustion termination system for the 120-in.-diameter (Titan III-C) solid rocket motor (SRM). The program was subsequently modified to include further study of the fundamental phenomena involved in the combustion termination process and the development of injector techniques and grain configurations applicable to the extinguishment of all types of segmented SRMs.

During the course of the program, a total of 56 motor firings was conducted to evaluate injectant materials, injection systems, and propellant charge configurations. These tests were conducted in motors ranging in size from a 0.5-lb laboratory motor to a two-segment TM-3A motor containing over 500 lb of propellant. In addition, 22 cold-flow tests were conducted to investigate injectant dispersion patterns of various injector configurations.

As a result of these tests, it was established that solid propellant motors cast with PBAN (polybutadiene acrylonitrile) propellant could be extinguished by injecting a liquid into the combustion chamber. The mechanism controlling the extinguishment of PBAN was determined to be heat transfer. For this reason, water, with its high specific heat, proved to be the most effective injectant, and the necessity of contacting all burning surfaces by the injectant was established. Radial slots in the propellant charge downstream of the injector were found to be particularly difficult to contact with injectant and were therefore subject to reignition. For this reason, a reliable system for extinguishing the Titan III-C was not developed.

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